IEEE 3000 STANDARDS COLLECTION™

IEEE 3006 STANDARDS:
POWER SYSTEMS RELIABILITY

Historical Reliability Data for IEEE 3006 Standards: Power Systems Reliability

IEEE STANDARDS ASSOCIATION

IEEE

IEEE 3000 Standards Collection™
for Industrial & Commercial Power Systems

Historical Reliability Data for IEEE 3006 Standards: Power Systems Reliability

Compiled by the

Technical Books Coordinating Committee
of the
IEEE Industry Applications Society

Abstract: Reliability data gathered from equipment reliability surveys and analyses over a period of 35 years or more is summarized in this collection. Equipment surveys conducted prior to 1976, detailed reports on the surveys and data collection efforts, and extensive lists of references on equipment reliability are presented. The collection provides the analyst with options for determining reliability parameters for older electrical systems.

Keywords: commercial power systems, electrical interruptions, IEEE Gold Book™ annex, historical reliability data, IEEE 3006, industrial power systems, outage data, power systems reliability, reliability analysis, reliability survey

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Print: ISBN 978-0-7381-7563-8 STDVAPD95897
PDF: ISBN 978-0-7381-7562-1 STDVA95897

Notice to users

Laws and regulations

Users of IEEE-SA documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE-SA document does not imply compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Copyrights

This document is copyrighted by the IEEE. It is made available for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making this document available for use and adoption by public authorities and private users, the IEEE does not waive any rights in copyright to this document.

Photocopies

Authorization to photocopy portions of any individual document for internal or personal use is granted by The Institute of Electrical and Electronics Engineers, Inc., provided that the appropriate fee is paid to Copyright Clearance Center. To arrange for payment of licensing fee, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual document for educational classroom use can also be obtained through the Copyright Clearance Center.

Foreword

Compiled in this collection of historical reliability data is invaluable information supporting the planning and design of industrial and commercial electric power distribution systems. It is a compilation of historical survey information collected through the efforts of Don Koval and Charles Heising over a period of approximately 35 years. This is a tribute to them and all of the contributors that made IEEE Std 493™ *(IEEE Gold Book™)* one of the best in what was the IEEE Color Book® series.

This collection summarizes the reliability information collected from equipment reliability surveys over a period of 35 years or more. It consists of equipment surveys conducted prior to 1976, detailed reports on the surveys and data collection efforts, and extensive lists of references on equipment reliability. Selected reliability and availability numeric from the survey efforts are also presented in this document.

This document provides the analyst with options for determining reliability parameters for older electrical systems. Data not found anywhere else is the cornerstone of this document, with some surveys spanning many years. In addition, there is utility numeric critical to facility assessments that identifies available power.

Robert G. Arno, *Senior Member of IEEE*

This collection is respectfully dedicated to Don Koval and Charles Heising, who devoted countless hours to compiling this data for the benefit of the industry.

Contents

Report on Reliability Survey of Industrial Plants

Part I
Reliability of Electrical Equipment

Part II
Cost of Power Outages, Plant Restart Time, Critical Service Loss Duration Time, and Type of Loads Lost Versus Time of Power Outages

Part III
Causes and Types of Failures of Electrical Equipment, the Methods of Repair, and the Urgency of Repair

By
Reliability Subcommittee
Industrial and Commercial Power Systems Committee
IEEE Industry Applications Society

W. H. Dickinson, *Chair*

P. E. Gannon
M. D. Harris
C. R. Heising
D. W. McWilliams
R. W. Parisian
A. D. Patton
W. J. Pearce

Industrial and Commercial Power Systems Technical Conference
Institute of Electrical and Electronics Engineers, Inc.
Atlanta, Georgia
May 13–16, 1973

Published by
IEEE Transactions on Industry Applications
March/April 1974

Report on Reliability Survey of Industrial Plants, Part I: Reliability of Electrical Equipment

IEEE COMMITTEE REPORT

Abstract—**An IEEE sponsored survey of electrical equipment reliability in industrial plants was completed during 1972. The results are reported from this survey which included a total of 1982 equipment failures that were reported by 30 companies covering 68 plants in nine industries in the United States and Canada.**

Introduction

A KNOWLEDGE of the reliability of electrical equipment is an important consideration in the design of power distribution systems for industrial plants. It is possible to make quantitative reliability comparisons between alternative designs of new systems and then use this information in cost–reliability tradeoff studies to determine which type of power distribution systems to use [1]–[10]. The cost of power outages at the various plant locations can be factored into the decision as to which type of power distribution system to use. These decisions can then be based upon total owning cost over the useful life of the equipment rather than first cost.

In 1969 a Reliability Working Group was formed under the Industrial Plants Power Systems Subcommittee, Industrial and Commercial Power Systems Committee. In 1972 the activity was changed to a Reliability Subcommittee under the same Committee. One of the major activities of the Reliability Working Group and the Reliability Subcommittee has been to conduct a survey of equipment reliability in industrial plants. This survey was conducted during the latter half of 1971 and the early part of 1972 and attempted to update a similar survey [11] which had been conducted eleven years ago. The results from the present survey contain data on failure rate and average downtime per failure for 74 equipment categories. The Reliability Subcommittee also felt that additional information was needed in the present survey beyond what was collected twelve years ago. Some of the additional information is the following:

1) cost of power outages of industrial plants;
2) plant restart time;
3) critical service loss duration time;
4) type of loads lost versus time of power outages;
5) repair or replacement time data;
6) repair urgency information;
7) causes and types of failures;
8) maintenance data and policies.

It is not practical to publish all the results contained in the survey in a single paper. They will be presented in six separate parts. The first three parts are published at this time

Part 1: Reliability of Electrical Equipment;
Part 2: Cost of Power Outages, Plant Restart Time, Critical Service Loss Duration Time, and Type of Loads Lost Versus Time of Power Outages [11];
Part 3: Causes and Types of Failures, Methods of Repair, and Urgency of Repair [12].

A major part of the data in these three papers are presented in summary form. It is expected that the additional three papers will be presented at a later date and will contain further in-depth information where questions have been raised to point out the need for such data.

Survey Form

The survey form is shown in Appendix A. Three types of cards were used for reporting the information.

Card type 1 asks for data on plant identification and other general plant information.

Card type 2 asks for data on a specific equipment class, including the total number of installed units, on their failure experience, on maintenance practices, and on estimated repair times of failed equipment.

Card type 3 asks for data on each individual failure reported on a card type 2.

It was necessary to provide definitions for "failure" and "repair time."

A *failure* is defined as any trouble with a power system component that causes any of the following to occur:

1) partial or complete plant shutdown, or below-standard plant operation;
2) unacceptable performance of user's equipment;
3) operation of the electrical protective relaying or emergency operation of the plant electrical system;
4) de-energization of any electric circuit or equipment.

A failure on a public utility supply system may cause the user to have either 1) a power interruption or loss of service, or 2) a deviation from normal voltage or frequency of sufficient magnitude or duration to disrupt plant production. A failure on an in-plant component causes a forced outage of the compo-

Paper TOD-73-158, approved by the Industrial and Commercial Power Systems Committee of the IEEE Industry Applications Society for presentation at the 1973 Industrial and Commercial Power Systems Technical Conference, Atlanta, Ga., May 13–16. Manuscript released for publication November 5, 1973.

Members of the Reliability Subcommittee of the IEEE Industrial and Commercial Power Systems Committee are W. H. Dickinson, *Chairman*, P. E. Gannon, M. D. Harris, C. R. Heising, D. W. McWilliams, R. W. Parisian, A. D. Patton, and W. J. Pearce.

nent, and the component thereby is unable to perform its intended function until it is repaired or replaced.

Repair time of a failed component or duration of a failure is the clock hours from the time of the occurrence of the failure to the time when the component is restored to service, either by repair of the component or by substitution with a spare component. It is not the time required to restore service to a load by putting alternate circuits into operation. It includes time for diagnosing the trouble, locating the failed component, waiting for parts, repairing or replacing, testing, and restoring the component to service.

Response to Survey

A total of 30 companies responded to the survey questionnaire, reporting data on 68 plants from nine industries in the United States and Canada as shown in Table I. There was a total of 1982 equipment failures reported in the survey; this included more than 620 000 unit-years of experience. Many of the plants reported data covering more than one year of experience.

Most of the data were reported to the IEEE Reliability Subcommittee during late 1971 and early 1972. Unfortunately, a downturn in the business cycle during this period of time caused many companies to reduce their work force and because of this fewer were able to participate in the survey than had been originally hoped.

Survey Data Preparation

All of the returned survey questionnaire forms were reviewed. An attempt was made to clarify any discrepancies that were detected. Usable data were punched onto IBM cards for use in data processing.

Statistical Analysis of Equipment Failures

Two equipment parameters are of prime importance in making system reliability studies. These parameters are 1) failure rate and 2) average outage duration or repair time. The best estimate for the failure rate of a particular type of equipment is the number of failures actually observed, divided by the total exposure time in unit-years, that is,

$$\hat{\lambda} = \frac{f}{T} \tag{1}$$

where

- $\hat{\lambda}$ best estimate of failure rate in failures per unit-year
- λ true failure rate
- f number of failures observed
- T total exposure time in unit-years.

Statements regarding the accuracy of failure rate estimates can be made through the use of confidence limits [10], [14]-[17]. Failure rate confidence limits are upper and lower values of failure rate such that the following equations hold:

$$\Pr\,[\lambda_L \geqq \lambda] = \frac{1-\gamma}{2} \tag{2}$$

$$\Pr\,[\lambda \geqq \lambda_U] = \frac{1-\gamma}{2} \tag{3}$$

where

- λ_L lower confidence limit of failure rate
- λ_U upper confidence limit of failure rate
- γ confidence interval (or confidence level).

A typical value often chosen for the confidence interval is 0.90. Once values for λ_L and λ_U are found, one can say that λ, whose best estimate is $\hat{\lambda}$, lies between λ_L and λ_U with 100γ percent confidence. Clearly the narrower the interval between λ_L and λ_U, the greater one's confidence that $\hat{\lambda}$ is a good estimate of λ, the true failure rate. Expressions for λ_L and λ_U are given as follows [17]:

$$\lambda_L = \frac{\chi^2 (1-\gamma)/2, 2f}{2T} \tag{4}$$

$$\lambda_U = \frac{\chi^2 (1+\gamma)/2, 2f+2}{2T} \tag{5}$$

where $\chi^2 p, n$ is the p percentage point of a chi-squared distribution with n degrees of freedom. $\chi^2 p, n$ is tabled in statistical handbooks.

By substituting the value of T from (1) into (4) and (5) we get

$$\lambda_L = \frac{\chi^2 (1-\gamma)/2, 2f}{2f} (\hat{\lambda}) \tag{6}$$

$$\lambda_U = \frac{\chi^2 (1+\gamma)/2, 2f+2}{2f} (\hat{\lambda}). \tag{7}$$

The deviation of the lower confidence level from $\hat{\lambda}$ in percent of $\hat{\lambda}$ is

$$\%\text{dev}_L = 100 \left(1 - \frac{\lambda_L}{\hat{\lambda}}\right). \tag{8}$$

Similarly, the deviation of the upper confidence level from $\hat{\lambda}$ in percent of $\hat{\lambda}$ is

$$\%\text{dev}_U = 100 \left(\frac{\lambda_U}{\hat{\lambda}} - 1\right). \tag{9}$$

Equations (6)-(9) were used to develop Fig. 1. These curves avoid the need of looking up $\chi^2 p, n$. Here λ_L and λ_U are plotted in terms of percent deviation from λ as a function of the observed number of failures.

The best estimate for the average outage duration or repair time for a particular type of equipment is simply the average of the observed outage durations. Confidence limit expressions for average outage durations are also available if the distributional nature of outage durations is known [17]. However, such expressions are not given here primarily because the average outage durations given in this paper are intended as a rough guide only. Equipment outage durations are believed to be more a function of the nature of a power system's operator than an inherent function of the equipment itself. Hence, average outage durations for equipment used in reliability studies should be values believed most reasonable for the particular system being studied.

The data from the survey contained information on the failure and repair characteristics of 217 categories of equipment. However, the number of observed failures for many equipment categories was too small to allow adequately accurate estimates of failure rates to be made. The Reliability Subcommittee felt that a minimum of eight to ten observed failures was required for "good" accuracy when estimating equipment failure rates (see Fig. 1). Therefore, whenever possible and reasonable from an engineering point of view, equipment categories having less than ten observed failures were combined with other categories so as to bring the number of observed failures in the combined category up to a minimum of ten. In some cases an equipment category with a large number of

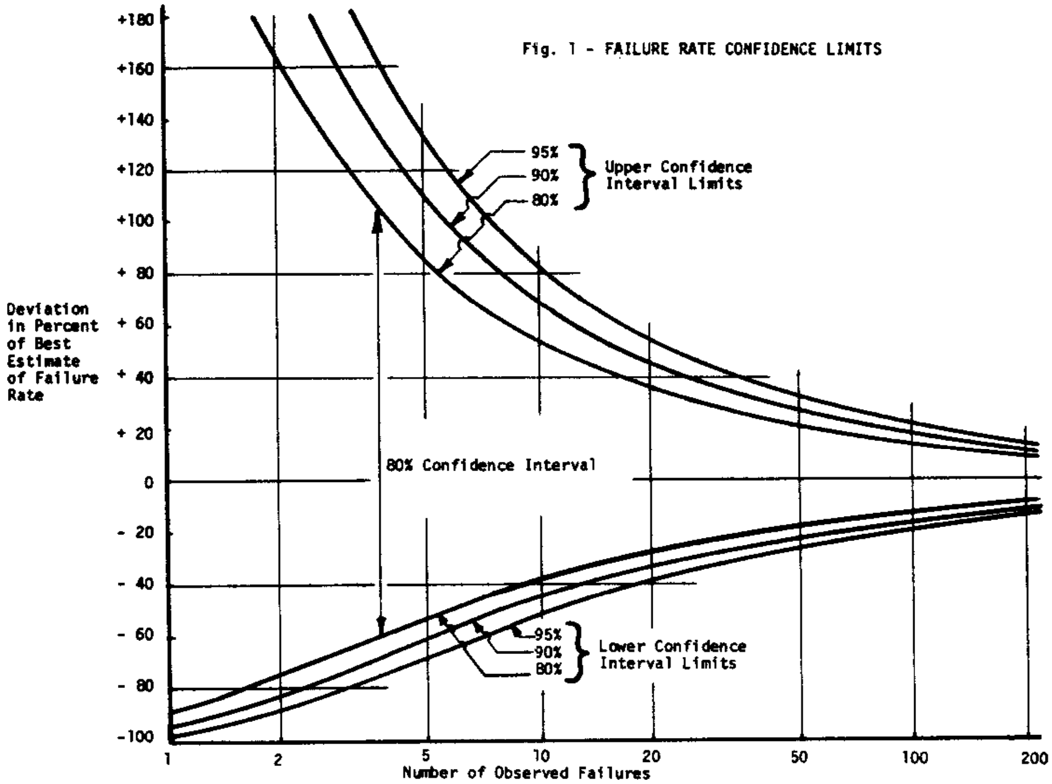


TABLE 1 - RESPONSE TO SURVEY QUESTIONNAIRE

Type of Industry	Number of Companies	Number of Plants
All Industry - USA & Canada	30*	68
Auto	0	0
Cement	0	0
Chemical	8	21
Metal	3	3
Mining	0	0
Petroleum	5	8
Pulp and Paper	1	1
Rubber & Plastics	3	3
Textile	1	3
Other Light Manufacturing	4	17
Other Heavy Manufacturing	1	2
Other	9	10
Foreign	1	1

*Some companies include more than one industry

observed failures was further subdivided. In most cases the equipment size attribute was eliminated by combining categories that were identical except for equipment size. These steps reduced the original 217 equipment categories to the 74 categories published in this paper. A total of 66 equipment categories have eight or more observed failures each; the other eight categories have between four and seven observed failures each.

Survey Results of Equipment Failures

Table 2 gives a summary of the "All Industry" equipment failure rate and equipment outage duration data for the 66 equipment categories that contain eight or more failures. The "actual hours downtime per failure" is based upon the actual outage data of the failed equipment; the "industry average" uses all equipment failures, and the "median plant average" uses all plants that reported actual outage time data on equipment failures.

The 1962 survey [11] contained equipment outage duration data on failures that have been challenged for two reasons.

1) Repairing a failed component may take much longer than replacing with a spare (for example, a large power transformer).

2) The urgency for repair is a significant factor in the outage time (low priority repairs may take days or weeks).

In order to help correct these deficiencies, two additional columns on "repair" and "replace with spare" were included in the survey and contain average estimated clock hours to fix failure during a 24-hour work day. These estimates are averaged over all the plants participating in the survey, even where there were no actual failures. These results are reported in Table 2 and are not included in the more detailed Tables 3-19.

Tables 3-19 give more detailed data on equipment failure rate and actual hours of equipment downtime per failure for 74 equipment categories; this includes the 66 equipment categories in Table 2 plus the eight equipment categories containing from four to seven failures. The additional detail includes

1) sample size in unit years;
2) number of failures;
3) number of plants reporting data;
4) additional data on actual hours of downtime per failure;
5) data for various industry groups where there were ten or more failures in that industry.

The data on average estimated clock hours to fix failure during 24-hour work day have been omitted from Tables 3-19.

The reliability data in Tables 14, 16, and 18 on cables, joints, and terminations represent a different look at the same data that are contained in Tables 13, 15, and 17. One set of tables looks at the type of insulation and the other set of tables looks at the application of the cable.

General Comments and Discussion

A survey that collects data from many plants often contains errors. Some of the errors are due to a misinterpretation of the question by the respondent, and in other cases they can be caused by omission.

Many of the respondents apparently misinterpreted the question on "number of installed units" for double- or triple-circuit electric utility power supplies. In addition, there was some confusion on the outage time after a failure of a single circuit of a double- or triple-circuit utility power supply. See the separate discussion elsewhere in this paper on these points. These are the only known major problems of misinterpretation of survey questions.

It is suspected that the failure rate estimates may be biased on the high side due to the tendency of companies to report only on equipment that has actually experienced failures. In other words, some companies may have omitted submitting unit-years of experience data on equipment that had no failures. This factor may be partially balanced out by the belief that the companies that participated in the survey may be the ones that have the best maintenance programs and keep the best records and thus may have lower failure rates than the average.

It is expected that a future paper will contain a comparison of the equipment reliability from this survey with the results from the previous survey [11] that was published in 1962. A preliminary comparison has been made and shows the following overall conclusion for 1973 versus 1962.

1) The 1973 equipment failure rates are about 0.6 times the 1962 failure rates.

2) The 1973 average downtime per failure is about 1.6 times the 1962 average downtime per failure.

3) The product of failure rate times average downtime per failure is almost the same in 1973 as 1962.

Both of these parameters are within a factor of two; and this is often the best accuracy that can be expected from reliability data.

How accurate are the failure rates shown in Tables 2-19? Fig. 1 shows the upper and lower confidence limits of the failure rate versus the number of failures observed. It can be seen that ten failures has upper and lower confidence limits of +70 percent and −46 percent for a 90 percent confidence interval. It is possible to determine the upper and lower confidence limits for the failure rate data shown in Tables 3-19.

Example of Confidence Limit Calculation

The use of Fig. 1 to determine confidence limits will be illustrated with an example. Suppose that it is desired to compute confidence limits on the failure rate of liquid-filled transformers with voltage above 15 kV in the chemical industry. The desired confidence interval is 90 percent. From Table 4, $\hat{\lambda} = 0.0119$ failures per unit-year, and the number of observed failures is 19. Entering Fig. 1 with 19 observed failures and using the 90 percent confidence interval curves yields

$$\lambda_L = \hat{\lambda} - 0.34\hat{\lambda}$$
$$= 0.0119 - 0.0041 = 0.0078 \text{ failures per unit-year}$$
$$\lambda_U = \hat{\lambda} + 0.46\hat{\lambda}$$
$$= 0.0119 + 0.0055 = 0.0174 \text{ failures per unit-year.}$$

There is a 90 percent chance that the true failure rate lies between 0.0078 and 0.0174 failures per unit-year.

TABLE 2 - SUMMARY OF "ALL INDUSTRY" EQUIPMENT FAILURE RATE AND EQUIPMENT OUTAGE DURATION DATA FOR 66 EQUIPMENT CATEGORIES CONTAINING 8 OR MORE FAILURES

Equipment	Equipment Sub Class	Failure Rate-Failures per Unit-Year	Actual Hours Downtime per Failure: Industry Average	Actual Hours Downtime per Failure: Median Plant Average	Average Estimated Clock Hours to Fix Failure During 24 Hour Work Day: Repair Failed Component	Average Estimated Clock Hours to Fix Failure During 24 Hour Work Day: Replace with Spare
Electric Utility Power Supplies..	All..................................	0.643	1.33	1.04	-	-
" " " "	Single Circuit.....................	0.537	5.66	5.10	-	-
" " " "	Double or Triple Circuit-All........	0.622	0.85	1.17	-	-
" " " "	Automatically Switched Over.......	0.735	0.59	0.93	-	-
" " " "	Manual Switchover................	0.458	1.87	2.00	-	-
" " " "...	Loss of All Circuits at One Time..	0.119	2.00	1.58	-	-
Transformers....................	Liquid Filled-All....................	0.0041	529.	219.	378.	73.4
"	601 - 15,000 Volts - All Sizes......	0.0030	174.	49.	382.	74.3
"	300-750 kVA.........................	0.0037	61.0	10.7	49.0	3.7
"	751-2,499 kVA....................	0.0025	217.	64.	297.	39.7
"	2,500 kVA & up...................	0.0032	216.	60.0	618.	150.
"	Above 15,000 Volts.................	0.0130	1076.	1260.	367.	71.5
"	Dry Type; 0 - 15,000 Volts...........	0.0036	153.	28.	67.	39.9
"	Rectifier; Above 600 Volts...........	0.0298	380.	80.	300.	20.0
Circuit Breakers................	Fixed Type ('ncl. molded case) - All..	0.0052	5.8	4.0	31.7	4.5
" "	0 - 600 Vo.ts - All Sizes...........	0.0044	4.7	4.0	6.0	2.0
" "	0 - 600 amps.....................	0.0035	2.2	1.0	4.0	2.0
" "	Above 600 amps...................	0.0096	9.6	8.0	8.0	2.0
" "	Above 600 Volts....................	0.0176	10.6	3.8	44.5	12.0
" "	Metalclad Drawout - All..............	0.0030	129.	7.6	54.2	3.9
" "	0 - 600 Volts - All sizes...........	0.0027	147.	4.0	47.2	2.9
" "	0 - 600 amps.....................	0.0023	3.2	1.0	75.6	1.2
" "	Above 600 amps...................	0.0030	232.	5.0	29.4	4.0
" "	Above 600 Volts....................	0.0036	109.	168.	62.4	5.2
Motor Starters..................	Contact Type; 0 - 600 Volts...........	0.0139	65.1	24.5	8.0	4.6
" "	Contact Type; 601 - 15,000 Volts......	0.0153	284.	16.0	23.6	13.8

TABLE 2 (Continued)

Equipment	Equipment Sub Class	Failure Rate - Failures per Unit-Year	Actual Hours Downtime per Failure: Industry Average	Actual Hours Downtime per Failure: Median Plant Average	Average Estimated Clock Hours to Fix Failure During 24 Hour Work Day: Repair Failed Component	Average Estimated Clock Hours to Fix Failure During 24 Hour Work Day: Replace with Spare
Motors...........................	Induction; 0 - 600 Volts..............	0.0109	114.	18.3	50.2	13.0
"	Induction; 601 - 15,000 Volts.........	0.0404	76.0	91.5	71.4	19.7
"	Synchronous; 0 - 600 Volts............	0.0007	35.3	35.3	32.0	10.0
"	Synchronous; 601 - 15,000 Volts.......	0.0318	175.	153.	146.	18.7
"	Direct Current - All..................	0.0556	37.5	16.2	69.0	5.3
Generators......................	Steam Turbine Driven..................	0.032	165.	66.5	234.	201.
"	Gas Turbine driven....................	0.638	23.1	92.0	190.	400.
Disconnect Switches.............	Enclosed..............................	0.0061	3.6	2.8	50.1	13.7
Switchgear Bus - Indoor & Outdoor	Insulated; 601 - 15,000 Volts.........	0.00170	261.	26.8	41.0	66.0
(Unit = Number of Connected	Bare; 0 - 600 Volts...................	0.00034	550.	24.0	41.5	24.5
Circuit breakers or Instrument	Bare; Above 600 Volts.................	0.00063	17.3	13.0	20.6	7.3
Transformer Compartments)						
Bus duct - Indoor & Outdoor...... (Unit = One Circuit Foot)	All Voltages..........................	0.000125	128.	9.5	12.9	6.0
Open Wire.......................	0 - 15,000 Volts......................	0.0189	42.5	4.0	4.6	8.0
(Unit = 1,000 Circuit Feet)...	Above 15,000 Volts....................	0.0075	17.5	12.0	8.0	-
Cable - All Types of Insulation.	Above Ground & Aerial					
(Unit = 1,000 Circuit Feet)...	0 - 600 Volts.......................	0.00141	457.	10.5	20.8	39.7
" "	601 - 15,000 volts - All............	0.01410	40.4	6.9	26.8	60.4
" "	In Trays Above Ground...........	0.00923	8.9	8.0	49.4	119.
" "	In Conduit Above Ground.........	0.04918	140.	47.5	-	19.8
" "	Aerial Cable....................	0.01437	31.6	5.3	10.6	28.0
" "	Below Ground & Direct Burial					
" "	0 - 600 Volts.......................	0.00388	15.0	24.0	-	26.8
" "	601 - 15,000 Volts - All............	0.00617	95.5	35.0	20.4	26.8
" "	In Duct or Conduit Below Ground...	0.00613	96.8	35.0	20.9	26.8
"	Above 15,000 Volts..................	0.00336	16.0	16.0	16.0	-

TABLE 2 (Continued)

Equipment	Equipment Sub Class	Failure Rate - Failures per Unit-Year	Actual Hours Downtime per Failure Industry Average	Actual Hours Downtime per Failure Median Plant Average	Average Estimated Clock Hours to Fix Failure During 24 Hour Work Day Repair Failed Component	Average Estimated Clock Hours to Fix Failure During 24 Hour Work Day Replace with Spare
Cable..........................	601 - 15,000 Volts					
(Unit = 1,000 Circuit Feet)...	Thermoplastic....................	0.00387	44.5	10.0	22.5	29.3
"	Thermosetting....................	0.00889	168.	26.0	27.2	55.2
"	Paper Insulated Lead Covered.....	0.00912	48.9	26.8	17.3	18.3
"	Other............................	0.01832	16.1	28.5	23.2	44.8
Cable Joints -All Types of Insul.	601 - 15,000 Volts					
" "	In Duct or Conduit Below Ground..	0.000864	36.1	31.2	14.7	5.5
Cable Joints....................	601 - 15,000 Volts					
" "	Thermoplastic....................	0.000754	15.8	8.0	12.6	22.0
" "	Paper Insulated Lead Covered.....	0.001037	31.4	28.0	30.0	-
Cable Terminations - All Types of Insulation.......	Above Ground & Aerial					
" " " "	0 - 600 Volts....................	0.000127	3.8	4.0	8.0	8.0
" " " "	601 - 15,000 Volts - All.........	0.000879	198.	11.1	34.6	40.6
" " " "	Aerial Cable.....	0.001848	48.5	11.3	15.3	18.0
" " " "	in Trays Above Ground.........	0.000333	8.0	9.0	48.8	58.3
" " " "	In Duct or Conduit Below Ground					
" "	601 - 15,000 Volts..............	0.000303	25.0	23.4	28.8	30.0
Cable Terminations.............	601 - 15,000 Volts					
	Thermoplastic.................	0.004192	10.6	11.5	12.0	12.0
" "	Thermosetting.................	0.000307	451.	11.3	30.2	42.8
" "	Paper Insulated Lead Covered...	0.000781	68.8	29.2	39.0	30.0
Miscellaneous..................	Inverters.......................	1.254	107.	185.	5.0	8.0
"	Rectifiers......................	0.038	39.0	52.2	41.5	12.0

TABLE 3 - ELECTRIC UTILITY POWER SUPPLIES

Number of Plants in Sample Size	Sample Size Unit - Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate - Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
30	314.4	202	All..............	All................................	0.643	1.33	*	1.04	24.0
7	70.8	38	"	Single Circuit....................	0.537	5.66	0.25	5.10	10.3
23	210.7	131	"	Double or Triple Circuit - All....	0.622	0.85	*	1.17	24.0
17	140.2	103	"	Automativally Switched Over.....	0.735	0.59	*	0.93	6.00
6	54.6	25	"	Manual Switchover..............	0.458	1.87	1.82	2.00	24.0
23	210.7	25	"	Loss of All Circuits At One Time	0.119	2.00	*	1.58	6.00
7	64.8	20	Chemical.........	All................................	0.309	1.42	*	1.58	6.00
7	64.8	20	"	Double or Triple Circuit - All....	0.309	1.42	*	1.58	6.00
6	60.1	20	"	Automatically Switched Over.....	0.333	1.42	*	1.58	6.00
3	46.5	10	Petroleum........	All................................	0.215	6.80	0.33	4.95	9.57
2	18.5	49	Textile..........	All................................	2.649	0.28	0.014	2.17	4.33
2	18.5	49	"	Double or Triple Circuit - All....	2.649	0.28	0.014	2.17	4.33
1	3.4	46	"	Automatically Switched Over.....	13.46	0.014	0.014	0.014	0.014
5	67.3	27	Other Light Manuf.	All................................	0.402	1.34	**	0.58	24.0
4	51.3	22	" " "	Double or Triple Circuit - All....	0.429	1.51	**	0.79	24.0
3	27.3	15	" " "	Automatically Switched Over.....	0.549	0.51	**	0.04	1.46

* 19 cycles
** 2 seconds

TABLE 4 - TRANSFORMERS

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry		Failure Rate - Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
33	15,210	63	All.............	Liquid Filled - All...	0.0041	529.	2.0	219.	3744.
30	13,210	39	"	601-15,000 volts - All Sizes....	0.0030	174.	2.0	49.	840.
12	3,002	11	"	300-750 kVA..................	0.0037	61.0	4.5	10.7	336.
18	6,040	15	"	751 - 2,499 kVA..............	0.0025	217.	2.0	64.0	840.
11	4,036	13	"	2,500 kVA & up................	0.0032	216.	24.0	60.0	403.
12	1,848	24	"	Above 15,000 volts.............	0.0130	1076.	12.8	1260.	3744.
16	4,937	18	"	Dry Type; 0-15,000 volts..........	0.0036	153.	0.5	28.	720.
3	672	20	"	Rectifier, Above 600 volts........	0.0298	380.	24.0	80.	867.
14	8,598	43	Chemical........	Liquid Filled - All..............	0.0050	338.	8.0	168.	1800.
12	6,838	24	"	601-15,000 volts - All Sizes....	0.0035	52.3	8.0	48.5	336.
7	3,274	10	"	300-750 kVA..................	0.0031	19.3	3.0	8.0	120.
9	1,601	19	"	Above 15,000 volts.............	0.0119	670.	12.8	708.	3600.
2	662	16	"	Rectifier; Above 600 volts........	0.0242	425.	80.0	474.	867.
3	2,512	14	Petroleum.......	Liquid Filled - All..............	0.0056	843.	4.5	591.	1178.
3	2,334	10	"	601-15,000 volts - All Sizes....	0.0043	244.	4.5	204.	403.

TABLE 5 - CIRCUIT BREAKERS

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry		Failure Rate - Failures per Unit-Year	Actual Hours Downtime/Failure			
						Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
16	9,501	49	All............	Fixed Type(includes molded case) - all	0.0052	5.8	0.5	4.0	72.0
12	8,990	40	"	0 - 600 volts - All Sizes...........	0.0044	4.7	0.5	4.0	11.0
9	7,643	27	"	0-600 amps........................	0.0035	2.2	0.5	1.0	9.0
4	1,347	13	"	Above 600 amps....................	0.0096	9.6	5.0	8.0	11.0
5	510	9	"	Above 600 volts.....................	0.0176	10.6	1.5	3.8	72.0
28	40,770	124	"	Metalclad, Drawout - All..............	0.0030	129.	0.3	7.6	890.
18	24,490	66	"	0-600 volts - All Sizes.............	0.0027	147.	0.2	4.0	894.
11	11,270	26	"	0-600 amps........................	0.0023	3.2	0.2	1.0	4.0
13	13,220	40	"	Above 600 amps....................	0.0030	232.	0.2	5.0	894.
22	16,280	58	"	Above 600 volts.....................	0.0036	109.	1.1	168.	883.
5	1,961	20	Chemical.......	Fixed Type(includes molded case) - All	0.0102	8.1	4.3	9.0	11.0
3	1,520	15	"	0-600 volts - All Sizes.............	0.0099	9.5	5.0	9.0	11.0
2	937	13	"	Above 600 amps....................	0.0139	9.6	5.0	8.0	11.0
7	10,850	33	"	Metalclad, Drawout - All..............	0.0030	83.7	5.8	97.7	576.
7	4,808	31	"	Above 600 volts.....................	0.0064	89.3	6.3	97.7	576.
3	1,885	18	Petroleum.......	Fixed Type(includes molded case) - All	0.0095	5.8	1.0	4.0	72.0
2	1,817	17	"	0-600 volts - All Sizes.............	0.0094	1.9	1.0	2.5	4.0
2	1,817	17	"	0-600 amps........................	0.0094	1.9	1.0	2.5	4.0
3	10,430	28	Textile.........	Metalclad, Drawout - All..............	0.0027	289.	0.3	4.0	890.
3	9,655	25	"	0-600 volts - All Sizes.............	0.0026	218.	0.3	4.0	894.
2	4,943	19	"	0-600 amps........................	0.0038	3.8	0.3	2.2	4.0

TABLE 6 - MOTOR STARTERS

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate - Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	maximum Plant Average
			All...........	Contact Type					
9	4,522	63	"	0-600 volts.........................	0.0139	65.1	1.0	24.5	75.5
15	6,518	100	"	601-15,000 volts....................	0.0153	284.	3.0	16.0	1440.
3	854	5	"	Circuit Breaker......................	0.0059	2.8	2.8	2.8	2.8
7	5,340	14	Chemical......	Contact Type; 601-15,000 volts........	0.0026	298.	4.5	16.0	1323.
1	207	51	Metal.........	Contact Type; 0-600 volts.............	0.2470	75.5	75.5	75.5	75.5
2	626	81	Petroleum.....	Contact Type; 601-15,000 volts........	0.1294	1440.	1440.	1440.	1440.

TABLE 7 - MOTORS

Number of Plants in Sample Size	Sample Size Unit-YEars	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate - Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
			All...............	Induction					
17	19,610	213	"	0-600 volts......................	0.0109	114.	0.5	18.3	312.
17	4,229	171	"	601-15,000 volts.................	0.0404	76.0	3.3	91.5	191.
			"	Synchronous					
2	13,790	10	"...............	0-600 volts......................	0.0007	35.3	35.3	35.3	35.3
11	4,276	136	"	601-15,000 volts.................	0.0318	175.	8.0	153.	360.
6	558	31	"	Direct Current.....................	0.0556	37.5	4.0	16.2	139.
			Chemical..........	Induction					
6	9,638	50	"	0-600 volts.............	0.0052	22.5	6.	10.3	45.7
8	2,819	122	"	601-15,000 volts........	0.0433	56.3	3.3	38.	191.
			"	Synchronous					
1	13,750	10	"	0-600 volts.............	0.0007	35.3	35.3	35.3	35.3
4	1,201	52	"	601-15,000 volts........	0.0433	129.	25.8	113.	218.
			Petroleum.........	Induction					
3	6,467	146	"	0-600 volts.............	0.0226	158.	120.	139.	159.
2	1,015	34	"	601-15,000 volts........	0.0335	139.	90.	119.	147.
			"	Synchronous					
2	2,826	78	"	601-15,000 volts........	0.0276	207.	167.	210.	254.
			Rubber & Plastics.	Induction					
3	161	12	" "	601-15,000 volts........	0.0748	144.	132	150.	168.
1	161	17	Textile...........	Direct Current............	0.1056	9.4	9.4	9.4	9.4

TABLE 8 - GENERATORS

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate - Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
8	761.8	24	All.............	Steam Turbine Driven......	0.032	165.	1.5	66.5	1080.
4	89.4	57	"..............	Gas Turbine Driven........	0.638	23.1	5.0	92.0	720.
4	59.4	4	"..............	Driven by Motor, Diesel, or Gas Engine.............	0.067	127.	121.	133.	144.
1	5.5	54	Petroleum.......	Gas Turbine Driven............	9.818	5.0	5.0	5.0	5.0

TABLE 9 - DISCONNECT SWITCHES

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate - Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
8	2,065	6	All...............	Open......................	0.0029	183.	3.0	6.0	1080.
16	15,490	94	"	Enclosed.................	0.0061	3.6	0.2	2.8	9.3
4	2,205	22	Chemical..........	Enclosed.................	0.0100	6.0	2.0	5.1	6.5
1	4,293	61	Metal.............	Enclosed.................	0.0142	2.8	2.8	2.8	2.8

TABLE 10 - SWITCHGEAR BUS: INDOOR & OUTDOOR
(Unit = Number of Connected Circuit Breakers or Instrument Transformer Compartments)

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate - Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
12	11,740	20	All.............	Insulated; 601-15,000 volts....	0.00170	261.	5.0	26.8	1613.
			"	Bare					
12	32,280	11	"	0-600 volts...............	0.00034	550.	2.0	24.0	2520.
5	20,560	13	"	Above 600 volts...........	0.00063	17.3	6.9	13.0	48.
5	4,003	15	Chemical........	Insulated; 601-15,000 volts.	0.00375	340.	18.0	26.8	1613.
			"	Bare					
3	17,270	10	"	Above 600 volts...........	0.00058	19.3	6.9	42.0	48.

TABLE 11 - BUS DUCT: INDOOR & OUTDOOR
(Unit = 1 Circuit Foot)

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate - Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
12	160,400	20	All...........	All Voltages...............	0.000125	128.	0.5	9.5	2160.

TABLE 12 - OPEN WIRE
(Unit = 1,000 Circuit Feet)

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate-Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
10	5,185	98	All..................	0-15,000 volts..........	0.0189	42.5	1.0	4.0	3600.
7	1,460	11	"	Above 15,000 volts........	0.0075	17.5	0.4	12.0	48.
3	292.6	10	Chemical.............	0-15,000 volts............	0.0342	606.	4.0	7.5	3600.
1	2,121	76	Petroleum...........	0-15,000 volts............	0.0358	4.1	4.1	4.1	4.1

TABLE 13 - CABLE (ALL TYPES OF INSULATION)
(Unit = 1,000 Circuit Feet)

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment SUb Class	Failure Rate-Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant average
			All.................	Above Ground & Aerial					
10	5,692	8	"	0-600 volts......................	0.00141	457.	2.0	10.5	1802.
18	5,248	74	"	601-15,000 volts - All...........	0.01410	40.4	0.2	6.9	360.
7	1,517	14	"	In Trays Above Ground..........	0.00923	8.9	6.0	8.0	12.7
6	183	9	"	In Conduit Above Ground........	0.04918	140.	4.0	47.5	360.
11	3,548	51	"	Aerial Cable...................	0.01437	31.6	0.2	5.3	178.
			"	Below Ground & Direct Burial					
3	2,060	8	"	0-600 volts.....................	0.00388	15.0	8.0	24.0	48.0
26	19,120	118	"	601-15,000 volts - All...........	0.00617	95.5	0.3	35.0	4320.
26	18,940	116	"	In Duct or Conduit Below Ground	0.00613	96.8	0.3	35.0	4320.
1	2,975	10	"	Above 15,000 volts...............	0.00336	16.0	16.0	16.0	16.0
			Chemical............	Above Ground & Aerial					
7	1,961	44	"	601-15,000 volts - All...........	0.02244	35.5	2.0	4.7	154.
3	1,137	11	"	In Trays Above Ground..........	0.00968	7.8	6.0	7.0	8.0
5	737	28	"	Aerial Cable...................	0.03800	47.1	2.0	4.7	178.
			"	Below Ground & Direct .urial					
10	11,420	70	"	601-15,000 volts - All...........	0.00613	53.0	2.6	25.0	514.
10	11,420	70	"	In Duct or Conduit Below Ground	0.00613	53.0	2.6	25.0	514.
			Petroleum..........	Above Ground & Aerial					
2	2,838	15	"	601-15,000 volts - All...........	0.00529	21.0	7.7	27.7	47.6
2	2,669	12	"	Aerial Cable...................	0.00450	23.1	7.7	53.8	100.
			"	Below Ground & Direct Burial					
2	981	23	"	601-15,000 volts - All...........	0.02345	94.0	26.8	69.7	113.
2	981	23	"	In Duct or Conduit Below Ground	0.02345	94.0	26.8	69.7	113.
1	2,975	10	"	Above 15,000 volts...............	0.00336	16.0	16.0	16.0	16.0

TABLE 14 - CABLE (ALL APPLICATIONS)
(Unit = 1,000 Circuit Feet)

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate-Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
			All..................	601-15,000 volts					
9	9,819	38	"	Thermoplastic.................	0.00387	44.5	2.0	10.0	178.
15	5,960	53	"	Thermosetting.................	0.00889	168.	0.2	26.0	4320.
10	7,126	65	"	Paper Insulated Lead Covered..	0.00912	48.9	0.3	26.8	120.
8	1,419	26	"	Other.........................	0.01832	16.1	0.7	28.5	168.
			Chemical.............	601-15,000 volts.					
7	9,158	36	"	Thermoplastic.................	0.00393	45.4	2.0	9.8	178.
3	2,578	26	"	thermosetting.................	0.01009	117.	17.3	202.	387.
4	937	26	"	Paper Insulated Lead Covered..	0.02774	10.7	2.6	25.0	120.
3	697	16	"	Other.........................	0.02297	18.3	8.0	9.0	168.
			Petroleum............	601-15,000 volts					
2	2,520	15	"	Thermosetting.................	0.00595	21.0	7.7	27.7	47.6
2	1,299	23	"	Paper Insulated Lead Covered..	0.01770	94.0	26.8	69.7	113.

TABLE 15 - CABLE JOINTS (ALL TYPES OF INSULATION)

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate-Failures per Unit-Year	Actual Hours Downtime/Failura Industry Average	minimum Plant Average	Median Plant Average	Maximum Plant Average
			All................	601-15,000 volts					
5	7,401	6	"	Above ground & Aerial..........	0.000811	20.3	8.0	16.5	48.0
12	40,500	35	"	In Duct or Conduit Below Ground	0.000864	36.1	1.0	31.2	160.
			Chemical...........	601-15,000 volts					
5	24,120	21	"	In Duct or Conduit Below Ground	0.000871	17.0	1.0	8.0	34.4

TABLE 16 - CABLE JOINTS (ALL APPLICATIONS)

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate-Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
			All................	601-15,000 volts					
5	27,860	21	"	Thermoplastic.................	0.000754	15.8	3.4	8.0	36.0
4	4,857	6	"	Thermosetting.................	0.001235	102.	14.0	60.0	160.
5	13,500	14	"	Paper Insulated Lead Covered...	0.001037	31.4	1.0	28.0	75.5
			Chemical............	601-15,000 volts					
4	22,900	20	"	Thermoplastic.................	0.000873	14.8	3.4	8.0	34.4

TABLE 17 - CABLE TERMINATIONS (ALL TYPES OF INSULATION)

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate-Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
			All................	Above Ground & Aerial					
4	63,120	8	"	0-600 volts..................	0.000127	3.8	0.5	4.0	5.9
13	39,840	35	"	601-15,000 volts - All.......	0.000879	198.	1.0	11.1	728.
4	24,010	8	"	In Trays Above Ground......	0.000333	8.0	7.0	9.0	11.0
3	3,920	5	"	In Conduit Above Ground....	0.001276	1157.	24.0	732.	1440.
7	11,910	22	"	Aerial Cable..............	0.001848	48.5	1.0	11.3	84.4
			"	In Duct or Conduit Below Ground					
6	26,390	8	"	601-15,000 volts............	0.000303	25.0	16.0	23.4	34.5
			chemical...........	Above Ground & Aerial					
7	25,790	21	"	601-15,000 volts - All.......	0.000814	284.	7.0	11.2	728.
4	1,677	9	"	Aerial Cable..............	0.005367	14.6	9.0	13.7	24.0
			Petroleum..........	Above Ground & Aerial					
2	10,150	12	"	601-15,000 volts - All.......	0.001182	79.3	24.0	54.2	84.4
1	10,120	11	"	Aerial cable..............	0.001087	84.4	84.4	84.4	84.4

TABLE 18 - CABLE TERMINATIONS (ALL APPLICATIONS)

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate-Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
			All............	601-15,000 volts					
2	2,385	10	"	Thermoplastic...............	0.004192	10.6	7.0	11.5	16.0
9	42,310	13	"	Thermosetting...............	0.000307	451.	9.3	11.3	1440.
5	20,490	16	"	Paper Insulated Lead Covered.	0.000781	68.8	16.0	29.2	82.6

TABLE 19 - MISCELLANEOUS

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry	Equipment Sub Class	Failure Rate-Failures per Unit-Year	Actual Hours Downtime/Failure Industry Average	Minimum Plant Average	Median Plant Average	Maximum Plant Average
5	3,164.	6	All...........	Fuses.......................	0.0019	5.5	1.0	2.0	24.0
3	30,600.	6	"	Protective Relays...........	0.0002	5.0	0.5	3.8	7.2
3	11.2	14	"	Inverters...................	1.25	107.	2.1	185.	369.
3	314.	12	"	Rectifiers..................	0.0382	39.0	32.4	52.2	72.0
2	5.6	14	Chemical.......	Inverters...................	2.51	107.	2.1	185.	369.
1	16.8	10	Petroleum......	Rectifiers..................	0.5970	32.4	32.4	32.4	32.4

APPENDIX A (P. 1 of

USER INSTRUCTIONS FOR IEEE SURVEY FORM ON
RELIABILITY OF ELECTRIC EQUIPMENT IN INDUSTRIAL PLANTS

(SPONSORED BY THE RELIABILITY WORKING GROUP,
INDUSTRIAL PLANTS POWER SYSTEMS SUBCOMMITTEE,
INDUSTRIAL AND COMMERCIAL POWER SYSTEMS COMMITTEE)

PURPOSE This survey is intended to collect data on failures that occur in in-plant electric equipment and in public utility electric power supplies that affect operations in industrial plants. We hope that these data will determine not only accurate failure rates and repair times on major classes of equipment, but will also give an insight into the causes of these failures in such a way that remedial recommendations may be formulated to reduce failures and to improve plant performance.

MAILING INSTRUCTIONS Mail all filled-out forms to the following address.

IEEE-IGA Reliability Working Group
Care of Assistant Professor A D Patton, Dept of Electrical Engineering
Texas A&M University
College Station, Texas 77843

DATA PROCESSING These forms will be given a confidential company code, and will then be key punched on cards for processing by a digital computer along with data collected from others. The computer will prepare a suitable report on failure rates, durations, and causes of failure.

ADDITIONAL INFORMATION The reverse side of the Survey Form asks for additional information. The following information should be filled in on the reverse side of the first page of data for each plant: company name, plant name, type and location, the name, address, and phone number of the individual submitting the data and/or the individual to whom questions about the data may be directed.

In addition, space is provided for remarks or clarifying comments on the data being reported. These comments should be filled in on all data sheets, if needed to clarify data.

DEFINITIONS

A component is a piece of equipment, a line or circuit, or a section of a line or circuit, or a group of items which is viewed as an entity.

A system is a group of components connected or associated in a fixed configuration to perform a specified function of generating, transmitting, or distributing power.

A failure is defined as any trouble with a power system component that causes any of the following to occur.

(1) Partial or complete plant shutdown, or below-standard plant operation
(2) Unacceptable performance of user's equipment
(3) Operation of the electrical protective relaying or emergency operation of the plant electrical system
(4) Deenergization of any electric circuit or equipment

A failure on a public utility supply system may cause the user to have either (1) a power interruption or loss of service, or (2) a deviation from normal voltage or frequency of sufficient magnitude or duration to disrupt plant production.

A failure on an in-plant component causes a forced outage of the component, and the component thereby is unable to perform its intended function until it is repaired or replaced.

Repair time of a failed component or duration of a failure is the clock hours from the time of the occurrence of the failure to the time when the component is restored to service, either by repair of the component or by substitution with a spare component. It is not the time required to restore service to a load by putting alternate circuits into operation.

It includes time for diagnosing the trouble, locating the failed component, waiting for parts, repairing or replacing, testing, and restoring the component to service.

Revision 3-4-71

2

USER INSTRUCTIONS FOR IEEE SURVEY FORM ON
RELIABILITY OF ELECTRIC EQUIPMENT IN INDUSTRIAL PLANTS
(SPONSORED BY THE RELIABILITY WORKING GROUP,
INDUSTRIAL PLANTS POWER SYSTEMS SUBCOMMITTEE,
INDUSTRIAL AND COMMERCIAL POWER SYSTEMS COMMITTEE)

GENERAL INSTRUCTIONS

THE SURVEY FORM The IEEE Survey Form 1' 1-70 is an input data form for a computer program. The data on these forms will be key punched onto computer cards and analyzed by the computer program.

CODED DATA The Survey Form asks for coded and uncoded data. It is necessary to refer to the instructions in filling in either. The following shows the columns on each card type that requires filling in a code.

CARD TYPE	COLUMNS REQUIRING CODES
1	1-10, 36
2	11-18, 33-36
3	25, 29, 30-53, 57, 58

It may happen that none of the codes shown fit the particular case being reported. For such cases, the "other" code should be used, by filling a "9" or a "99" in the space provided. "Other" means not otherwise classified. If this is done, explain on reverse side of page, referring to card type and column number.

EQUIPMENT CLASS A group of codes is used to specify an equipment class. An equipment class consists of a main code, two sub-class codes, a voltage code and a size code. These are explained in the instructions. For the example shown on the filled-out form, this code is as follows.

CLASS	CODE	DESCRIPTION
Main	20	= transformer
Sub 1	4	= power
Sub 2	34	= liquid filled
Voltage	2	= 601-15,000 volts primary
Size	3	= 300-750 kVA

The above coded equipment class covers all liquid-filled power transformers, with a primary voltage of 601-15,000 volts and rated 300-750 kVA. Any transformer in the plant that does not fit this example is a different classification and requires a different coding. Thus, a 5000 kVA power transformer, liquid filled, 13.8 kV primary voltage would be coded 20-4-34-2-5.

CARD-TYPES The Survey Form asks for three types of information under the headings CARD-TYPE 1, CARD-TYPE 2, and CARD-TYPE 3.

In general, CARD-TYPE 1 asks for data on plant identification and other general plant information.

CARD-TYPE 2 asks for data on a specific equipment class, including the total number of installed units, on their failure experience, on maintenance practices, and on estimated repair times of failed equipment. The total installed units and their failure experience is the most essential data asked for.

CARDS-TYPE 3 asks for data on each individual failure reported on a CARD-TYPE 2.

A typical plant might have as many as, say 30 different equipment classes. These 30 equipment classes might have, for example 10 different failures. To report this information requires 30 pages of the Survey Form, one for each different equipment class. CARD-TYPE 1 is filled in completely on the first page and partly thereafter. CARD-TYPE 2 is filled in on each page. CARDS-TYPE 3 are filled in 10 times, once for each failure, if any.

CARD-TYPE 1 CARD-TYPE 1 is used to identify the reporting company and plant of that company and to give general information about that plant. The first 10 columns on this card are to be repeated by the key puncher onto CARD-TYPE 2 and CARDS-TYPE 3 for identification purposes.

Only one CARD-TYPE 1 is used by the computer program. However, we ask that on each page of the IEEE Survey Form that the first 7 columns be filled-in in case the filled-out survey forms become separated.

Fill in Items 1-8 on reverse side of first page of data for each plant.

ALL CARD TYPES Fill in CARD-TYPE, column number, and remarks or comments on reverse side, if any, on all data cards.

MMD

APPENDIX A (P. 2 o

3

USER INSTRUCTIONS FOR IEEE SURVEY FORM ON
RELIABILITY OF ELECTRIC EQUIPMENT IN INDUSTRIAL PLANTS
(SPONSORED BY THE RELIABILITY WORKING GROUP,
INDUSTRIAL PLANTS POWER SYSTEMS SUBCOMMITTEE,
INDUSTRIAL AND COMMERCIAL POWER SYSTEMS COMMITTEE

CARD-TYPE 2 The second or CARD-TYPE 2 is used to report on each different equipment class in the plant. A typical plant might have a one type of utility supply, and several different classes each of transformers, circuit breakers, cables, etc. These different classes are shown in Columns 11-18. These Columns 11-18 are to be repeated by the key puncher on all CARDS-TYPE 3. There will be as many CARDS-TYPE 2 as there are different equipment classes.

Each CARD-TYPE 2 is used to report (1) the total number installed of one equipment class and the total number of failures experienced (if any) of that equipment class.

In addition, each CARD-TYPE 2 is used to report on maintenance practices and estimated repair times. These are your best estimate of repair times. These estimated times will be used if actual repair times are not known, or if actual repair times are much different from the average for some special reason which is unlikely to recur. We prefer to use actual data if available.

These data are to be left blank for failures on the utility power supply, since this information is not normally available.

CARD-TYPE 3 The third or CARD-TYPE 3 is used to report on actual data for each failure reported on a corresponding CARD-TYPE 2. Thus, associated with each CARD-TYPE 2 is a set of CARDS-TYPE 3. The number of CARDS-TYPE 3 will be the same as the number of failures (column 31) reported on CARDS-TYPE 2, for example, if a CARD-TYPE 2 has a 3 in Column 31, then 3 CARDS-TYPE 3 should be filled in.

Each CARD-TYPE 3 reports specific information on one failure, such as failure duration, urgency of repair, cause of failure, loads affected by the failure, and effect of failure on plant operations.

RIGHT-ADJUSTMENT OF DATA In filling in data, numbers should be right-adjusted, that is, they must end in the right-hand column of the assigned field. This means that if, for example, the survey form provides 3 columns to insert data but a two-digit number is to be inserted in the space available, then the number should be filled into the two right-hand columns.

SAMPLE FILLED-OUT FORM Refer to the attached sample filled-out form. This gives an example of a report on one class of transformers with two failures.

SAMPLE

7) DATE 3 - 4 - 71 · IEEE SURVEY FORM 11-1-70 PAGES 15 PAGE 4

RELIABILITY OF ELECTRIC EQUIPMENT IN INDUSTRIAL PLANTS

CARD – TYPE 1

(REFER TO SURVEY FORM INSTRUCTIONS)
(NOTE – * REFERS TO CODED DATA)

COMPANY CODE	PLANT*					PLANT OPERATING SCHEDULE		ESTIMATED PLANT OUTAGE COST, $		PLANT MAX. DEMAND AT PLANT DESIGN CAPACITY, KW	PLANT RESTART TIME, HOURS	CRITICAL SERVICE LOSS DURATION			CARD TYPE	CARD NO.
	NO.	TYPE	LOCATION	CLIMATE	ATMOSPHERE	HR. PER DAY	DAYS PER WK.	PER FAILURE	PER HR. DOWNTIME			NO. OF UNITS	UNITS*			
1	4	6	8	9	10	11	13	15	20	25	31	33	36		79	80
GEL	1	10	1	5	1	8	5	4000	2000	54000	2	10	4		1	1

CARD – TYPE 2

EQUIPMENT CLASS*					PERIOD COVERED BY THIS REPORT				NO. OF INSTALLED UNITS	NUMBER OF FAILURES	AVERAGE AGE*	MAINTENANCE		ESTIMATED CLOCK HOURS TO REPAIR A FAILURE				CARD TYPE	CARD NO.
					FROM		TO							REPAIR FAILED COMPONENT		REPLACE WITH SPARE			
MAIN	SUB 1	SUB 2	VOLTAGE	SIZE	MO.	YR.	MO.	YR.				NORMAL CYCLE, NO.	QUALITY	24-HR. PER DAY	8-HR. PER DAY	24-HR. PER DAY	8-HR. PER DAY		
11	13	15	17	18	19	21	23	25	27	31	33	34	36	37	41	45	48	79	80
20	4	34	2	3	1	66	10	70	120	2	3	3	2	100	300	14	48	2	1

CARDS – TYPE 3

FAILURE															LOADS LOST*					% PRODUCTION LOST*	PLANT OUTAGE DURATION		SERVICE RESTORED*	CARD TYPE	CARD NO.
NUMBER	DATE		FOREWARNING*	DURATION		REPAIR METHOD*	REPAIR URGENCY*	NO. SINCE LAST MAINTAINED*	DAMAGED PART*	TYPE*	RESPONSIBILITY*	INITIATING CAUSE*	CONTRIBUTING CAUSE*	CHARACTERISTICS*	COMPUTER	MOTOR	LIGHTING	SOLENOID	OTHER		NO. OF UNITS	UNITS*			
	MO.	YR.		NO. OF UNITS	UNITS*																				
19	21	23	25	26	29	30	32	34	36	38	40	42	44	46	48	49	50	51	52	53	54	57	58	79	80
1	9	69		60	2	2	1	2	9	1	1	4	99	15	1	1	1	1	1	2	4	4	4	3	1
2	8	70		180	2	1	1	3	2	1	5	99	10	6	1	1	0	9	1	2	4	4	4	3	2
3																								3	3
4																								3	4
5																								3	5
6																								3	6
7																								3	7
8																								3	8
9																								3	9
10																								3	0

MHD **APPENDIX A (P. 3 of 7)**

5

USER INSTRUCTIONS FOR CARD-TYPE 1

CARD - TYPE 1

(REFER TO SURVEY FORM INSTRUCTIONS)
(NOTE - * REFERS TO CODED DATA)

COMPANY CODE	PLANT* NO.	PLANT* TYPE	PLANT* LOCATION	PLANT* CLIMATE	PLANT* ATMOSPHERE	PLANT OPERATING SCHEDULE HR. PER DAY	PLANT OPERATING SCHEDULE DAYS PER WK.	ESTIMATED PLANT OUTAGE COST, $ PER FAILURE	ESTIMATED PLANT OUTAGE COST, $ PER HR. DOWNTIME	PLANT MAX. DEMAND AT PLANT DESIGN CAPACITY, KW	PLANT RESTART TIME, HOURS	CRITICAL SERVICE LOSS DURATION NO. OF UNITS	CRITICAL SERVICE LOSS DURATION UNITS*		CARD TYPE	CARD NO.
1	4	6	8	9	10	11	13	15	20	25	31	33	36		79	80
															1	1

COLUMN	NAME	CODE	DESCRIPTION
1	Company Code		Fill in on all pages a three-letter abbreviation of company name for identification of data.
4	Plant No		Fill in on all pages a sequence number starting with "1" for Plant 1, "2" for Plant 2, etc. for identification of data. A plant may consist of one or more units at the same site.
6	Plant Type		Fill in on all pages the plant type
		1	Auto Industry
		2	Cement Industry
		3	Chemical Industry
		4	Metal Industry
		5	Mining Industry
		6	Petroleum Industry
		7	Pulp and Paper Industry
		8	Rubber and Plastics Industry
		9	Textile Industry
		10	Other Light Manufacturing
		11	Other Heavy Manufacturing
		99	Other
8	Plant Location	1	USA and Canada
		2	Foreign
9	Plant Climate (For entire plant site)		Average of daily maximums for hottest month: Temperature / Relative Humidity (RH) (measured at noon to 2 PM ST)
		1	Hot (>90F) High (>55 RH)
		2	Hot (>90F) Moderate (50-55 RH)
		3	Hot (>90F) Low (<50 RH)
		4	Moderate (80-90F) High (>55 RH)
		5	Moderate (80-90F) Moderate (50-55 RH)
		6	MOderate (80-90F) Low (<50 RH)
		7	Low (<80F) High (>55 RH)
		8	Low (<80F) Moderate (50-55 RH)
		9	Low (<80F) Low (<50 RH)
10	Plant Atmosphere (For entire plant site)	1	Clean to slightly polluted air
		2	With salt spray and corrosive chemicals
		3	With salt spray and dust or sand
		4	With salt spray only
		5	With corrosive chemicals and dust or sand
		6	With corrosive chemicals only
		7	With dust or sand only
		8	With conductive dust
		9	Other
	Plant Operating Schedule		
11	Hours per day		Give hours per normal working day that plant operates
13	Days per week		Give days per normal working week that plant operates
	Estimated Plant Outage Cost, Dollars		
15	Per Failure		Extra expense incurred because of a failure only (not including plant downtime), such as for damaged equipment, spoiled product, extra maintenance, or extra repair costs

EB

6

USER INSTRUCTIONS FOR CARD-TYPE 1

CARD – TYPE 1

(REFER TO SURVEY FORM INSTRUCTIONS)
(NOTE – * REFERS TO CODED DATA)

COMPANY CODE	PLANT*					PLANT OPERATING SCHEDULE		ESTIMATED PLANT OUTAGE COST, $		PLANT MAX. DEMAND AT PLANT DESIGN CAPACITY, KW	PLANT RESTART TIME, HOURS	CRITICAL SERVICE LOSS DURATION			CARD TYPE	CARD NO.
	NO.	TYPE	LOCATION	CLIMATE	ATMOSPHERE	HR. PER DAY	DAYS PER WK.	PER FAILURE	PER HR. DOWNTIME			NO. OF UNITS	UNITS*			
1	4	6	8	9	10	11	13	15	20	25	31	33	36		79	80
															1	1

COLUMN	NAME	CODE	DESCRIPTION
20	Per hour downtime		Value of lost production in dollars per hour of plant downtime only. This is the estimated revenues (sales price) of product not made, less expenses saved in labor, material, utilities, etc. If this varies with the duration of the plant downtime, use an average value per hour.
25	Plant maximum demand at design capacity, kW		Give the maximum electric power demand when the plant is operating at its rated or design capacity in kilowatts.
31	Plant restart time, hours		Give the time required to get the plant back into operation after service is restored following a failure that has caused a complete plant shutdown, hours.
	Critical service loss duration		
33	No of units		Give the maximum time in units defined in Col 36 of loss of service to the plant which will not cause a complete plant shutdown. Any power interruption of longer duration will cause a plant shutdown. In other words, give maximum length of power failure that will not stop plant production. This time is typically in the range of cycles to minutes.
36	Units		Select code for appropriate time unit that will give accurate results.
		1	Days
		2	Hours
		3	Minutes
		4	Seconds
		5	Cycles

MRD

APPENDIX A (P. 4 of 7)

7

USER INSTRUCTIONS FOR CARD-TYPE 2

CARD - TYPE 2

EQUIPMENT CLASS*					PERIOD COVERED BY THIS REPORT				NO. OF INSTALLED UNITS	NUMBER OF FAILURES	AVERAGE AGE*	MAINTENANCE			ESTIMATED CLOCK HOURS TO REPAIR A FAILURE				CARD TYPE	CARD NO.
					FROM		TO								REPAIR FAILED COMPONENT		REPLACE WITH SPARE			
MAIN	SUB 1	SUB 2	VOLTAGE	SIZE	MO.	YR.	MO.	YR.				NORMAL	CYCLE MO.	QUALITY	24-HR. PER DAY	8-HR. PER DAY	24-HR. PER DAY	8-HR. PER DAY		
11	13	15	17	18	19	21	23	25	27	31	33	34		36	37	41	45	49	79	80
																			2	1

COLUMN	NAME	CODE	DESCRIPTION
			Select appropriate code for Column 11-18
11	Main Class	10	Utility power supplies to plant
		20	Transformers
		30	Circuit Breakers
		40	Cable (Excluding joints and terminations)
		41	Cable Joints
		42	Cable Terminations
		43	Cable Duct or Busway
		44	Open Wire
		45	Busduct
		46	Switchgear Bus -insulated
		47	Switchgear Bus -bare
		50	Motors
		60	Generators
		70	Motor Starters
		80	Disconnect Switches
		90	Miscellaneous
		99	Other
13	Sub Class 1		<u>For 10-Utility Power Supplies</u> (A redundant supply will carry the plant load, if the normal circuit is out of service)
		1	Single Circuit (No redundant supply)
		2	Double Circuit (One redundant supply)
		3	Three or more circuits (two or more redundant supplies)
			<u>For 20 - Transformers</u>
		4	Power
		5	Other
			<u>For 30-Circuit Breakers</u>
		6	Metal Clad, drawout
		7	Fixed Type (includes molded case type)
			<u>For 40-47 Cable or Bus</u>
		9	Cable in Trays - aboveground
		10	Cable in Conduit -aboveground
		11	Aerial Cable
		12	Direct Buried Cable
		13	Cable in Duct or Conduit -belowground
		14	Bus or Busduct -indoor
		15	Bus or Busduct -outdoor
			<u>For 50 - Motors</u>
		16	Induction, ac
		17	Synchronous, ac
		18	Direct-current
			<u>For 60 - Generators</u>
		19	Steam Turbine Driven
		20	Gas Turbine Driven
		21	Diesel or Gas Engine Driven
		22	Motor-driven
			<u>For 70 - Motor Starters</u>
		23	Contactor Type
		24	Circuit Breaker

8

USER INSTRUCTIONS FOR CARD-TYPE 2

CARD - TYPE 2

EQUIPMENT CLASS*					PERIOD COVERED BY THIS REPORT				NO. OF INSTALLED UNITS	NUMBER OF FAILURES	AVERAGE AGE*	MAINTENANCE		ESTIMATED CLOCK HOURS TO REPAIR A FAILURE				CARD TYPE	CARD NO.
					FROM		TO							REPAIR FAILED COMPONENT		REPLACE WITH SPARE			
MAIN	SUB 1	SUB 2	VOLTAGE	SIZE	MO.	YR.	MO.	YR.				NORMAL CYCLE, MO.	QUALITY	24-HR. PER DAY	8-HR. PER DAY	24-HR. PER DAY	8-HR. PER DAY		
11	13	15	17	18	19	21	23	25	27	31	33	34	36	37	41	45	49	79	80
																		2	1

COLUMN	NAME	CODE	DESCRIPTION
13	Sub Class 1 (Cont)		For 80 - Disconnect Switches
		25	Open
		26	Enclosed
			For 90 - Miscellaneous
		27	Fuses
		28	Protective relays
		29	Batteries
		30	Inverters
		31	Rectifiers
		99	Other
15	Sub Class 2		For 10-Utility Supplies When service is lost because of a loss of one circuit of a redundant supply service is restored
		1	Automatically
		2	By remote control
		3	Manually
			For 20 - Transformers
		34	Liquid Filled
		35	Dry Type
		38	Rectifier
			For 40-51 Cable Type of Insulation
		40	Thermoplastic (PVC)
		41	Thermoplastic (Polyethylene)
		42	Thermosetting (SBR (Buna S) Rubber)
		43	Thermosetting (Butyl Rubber)
		44	Thermosetting (Oil Based Rubber)
		45	Thermosetting (Cross-Linked Polyethylene)
		46	Thermosetting (Silicone Rubber)
		47	Thermosetting (Ethylene Propylene)
		48	Thermosetting (Chlorosulphated Propylene)
		49	Paper-Insulated Lead Covered
		50	Varnished Cambric Insulated-Lead Covered
		51	Mineral-Insulated
		99	Other (Applies to Col 13-15, all classes, if not otherwise classified)
17	Volt Class	1	0-600 volt (Note: For transformers this is primary voltage)
		2	601-15,000 volt
		3	Above 15,000 volt

APPENDIX A (P. 5 of

9

USER INSTRUCTION FOR CARD-TYPE 2

CARD – TYPE 2

EQUIPMENT CLASS*					PERIOD COVERED BY THIS REPORT				NO. OF INSTALLED UNITS	NUMBER OF FAILURES	AVERAGE AGE*	MAIN-TENANCE		ESTIMATED CLOCK HOURS TO REPAIR A FAILURE				CARD TYPE	CARD NO.
MAIN	SUB 1	SUB 2	VOLTAGE	SIZE	FROM		TO					NORMAL CYCLE, MO.	QUALITY	REPAIR FAILED COMPONENT		REPLACE WITH SPARE			
					MO.	YR.	MO.	YR.						24-HR. PER DAY	8-HR. PER DAY	24-HR. PER DAY	8-HR. PER DAY		
11	13	15	17	18	19	21	23	25	27	31	33	34	36	37	41	45	49	79	80
																		2	1

COLUMN	NAME	CODE	DESCRIPTION
18	Size Class		For Main Class 10 - Utility Supplies For Main Class 30 - Circuit Breakers For Main Class 80 - Disc Switches <u>For Main Class 90 - Miscellaneous, Fuses</u>
		1	100-600 Amperes
		2	Above 600 amperes
			<u>For Main Class 20 - Transformers</u>
		3	300-750 kVA
		4	751-2499 kVA
		5	2500-up kVA
			<u>For Main Class 40-45 - Cable, etc</u>
		6	Above No 1 AWG
			For Main Class 50 - Motors <u>For Main Class 70 - Motor Starters</u>
		7	50-1500 horsepower
		8	Above 1500 horsepower
			<u>For Main Class 60 - Generators</u>
		9	500-up kW
	Period covered by this report		Give month and year (numerals) for period for which failure data is available
19	From: Mo		Starting Month (Try to include data from date of installation)
21	From: Yr		Starting Year
23	To: Mo		Ending Month (Try to include data to date of this report)
25	To: Yr		Ending Year
27	No of installed units		Give total number of units installed. For cable or open wire, give length of circuit or run in M ft. For cable duct or busduct, give circuit length in feet. For switchgear bus, give the number of connected circuit breakers or instrument transformer compartments. For utility power supplies, give the number of separate supplies.
31	No of Failures		Give total number of failures that occurred during period of report. If more than 10 use additional page.
			<u>Select codes for Column 30-53</u>
33	Average Age	1	Less than 1 year old
		2	1-10 years old
		3	More than 10 years old
	Maintenance		Give normal cycle for preventive maintenance - (even if a failure has not occurred)
34	Normal Cycle, Mo	1	Less than 12 months
		2	12-24 months
		3	More than 24 months
		4	No preventive maintenance
36	Maintenance Quality		Your estimate of quality of preventive maintenance is -
		1	Excellent (by own forces)
		2	Fair (by own forces)
		3	Poor, inadequate (by own forces)
		4	None
		5	Excellent (by contracted forces)
		6	Fair (by contracted forces)
		7	Poor inadequate (by contracted forces)

WHD

10

USER INSTRUCTIONS FOR CARD-TYPE 2

CARD – TYPE 2

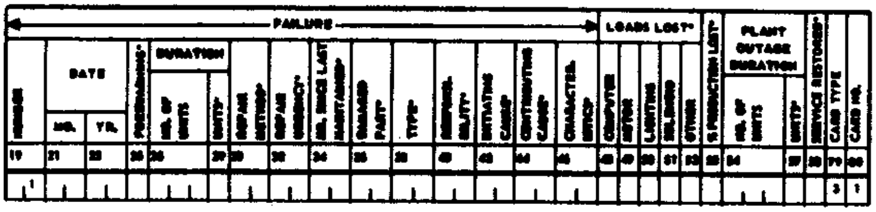
EQUIPMENT CLASS*					PERIOD COVERED BY THIS REPORT				NO. OF INSTALLED UNITS	NUMBER OF FAILURES	AVERAGE AGE*	MAIN-TENANCE		ESTIMATED CLOCK HOURS TO REPAIR A FAILURE				CARD TYPE	CARD NO.
					FROM		TO							REPAIR FAILED COMPONENT		REPLACE WITH SPARE			
MAIN	SUB 1	SUB 2	VOLTAGE	SIZE	MO.	YR.	MO.	YR.				NORMAL CYCLE, NO.	QUALITY	24-HR. PER DAY	8-HR. PER DAY	24-HR. PER DAY	8-HR. PER DAY		
11	13	15	17	18	19	21	23	25	27	31	33	34	36	37	41	45	48	79	80
																		2	1

COLUMN	NAME CODE	DESCRIPTION
	Estimated clock hours	Repair time (see definitions) Fill in the clock time for diagnosing the trouble, locating the failed component, waiting for parts repairing or replacing, testing and restoring the component to service. This is your estimate of the average repair time. Please note that actual repair times are requested in CARD-TYPE 3, Col 26. Explain on reverse side how work is done if by other than own forces.
	Repair failed component	With repair of failed equipment
37	24-hr per day	On round-the-clock emergency basis
41	8-hr per day	On basis of repair during normal work day
		With replacement of failed equipment with a spare by removal of failed equipment and substitution of spare equipment
	Repair with spare	
45	24-hr per day	On round-the-clock emergency basis
48	8-hr per day	On basis of repair during normal work day

11

USER INSTRUCTIONS FOR CARD-TYPE 3

CARDS - TYPE 3

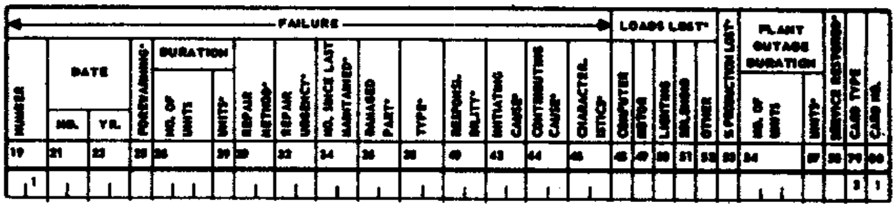


COLUMN	NAME	CODE	DESCRIPTION
19	Failure No		Fill in one card (line) for each failure. The last failure number in Col 19 should correspond with the total failures reported in Col 31 of CARD-TYPE 2. If that number was "0" then no TYPE 3 cards should be filled in.
	Failure Date		
21	Mo		Fill in month failure occured (numeral)
23	Yr		Fill in year failure occurred (numeral)
25	Failure Forewarning		For public utility power interruption only
		1	If no forewarning was given
		2	If forewarning was given
			For other types of failure, leave blank
	Failure Duration		Fill in duration of failure from its initiation until (1) service is restored to normal, if a power interruption, or (2) the affected component or its replacement once again becomes available to perform its intended function.
26	No of Units		Fill in the number of time units selected in Col 29.
29	Units		Select code for appropriate time unit that will give accurate results. For most cases select hours as unit.
		1	Days
		2	Hours
		3	Minutes
		4	Seconds
		5	Cycles
			Select code for Col 30-44 (Leave blank for utility failures)
30	Failure Repair Method	1	Repair of failed component in place or sent out for repair
		2	Repair by replacement of failed component with spare
32	Failure Repair Urgency	1	Requiring round-the-clock all out efforts
		2	Requiring repair work only during regular workday, perhaps with some overtime.
		3	Requiring repair work on a non-priority basis.
34	Failure, months since maintained		Failed component last had preventive maintenance -
		1	Less than 12 months ago
		2	12-24 months ago
		3	Over 24 months ago
		4	No preventive maintenance
36	Failure, Damaged Part	1	Insulation - winding
		2	Insulation - bushing
		3	Insulation - other
		4	Mechanical - bearings
		5	Mechanical - other moving parts
		6	Mechanical - other
		7	Other electrical - auxiliary device
		8	Other electrical - protective device
		9	Tap changer - no load type
		10	Tap changer - load type
		99	Other

12

USER INSTRUCTIONS FOR CARD-TYPE 3

CARDS - TYPE 3



COLUMN	NAME	CODE	DESCRIPTION
38	Failure Type	1	Flashover or arcing involving groun.[3]
		2	All other flashover or arcing
		3	Other electrical defect
		4	Mechanical defect
		99	Other
			Your best estimate of suspected responsibility
40	Failure Responsibility	1	Manufacturer-defective Component
		2	Transportation to Site - defective handling
		3	Application Engineering - improper application
		4	Inadequate installation and testing prior to startup
		5	Inadequate maintenance
		6	Inadequate operating procedures
		7	Outside agency -personnel
		8	Outside agency -other
		99	Other
42	Failure Initiating Cause		Insulation breakdown caused by
		1	Transient overvoltage disturbance (lightning, switching surges, arcing ground fault in ungrounded system)
		2	Overvoltage
		3	Overheating
		4	Other insulation breakdown
		21	Mechanical breaking, cracking, loosening, abrading, or deforming of static or structural parts
		22	Mechanical burnout, friction, or seizing of moving parts
		23	Mechanically caused damage from foreign source (digging, vehicular accident, etc)
		41	Shorting by tools or metal objects
		42	Shorting by birds, snakes, rodents, etc
		51	Loss of control power
		52	Malfunction of protective relay control device, or auxiliary device
		61	Low voltage
		62	Low frequency
		99	Other
44	Failure Contributing Cause	1	Persistent overloading
		2	Above-normal temperatures
		3	Below-normal temperature
		4	Exposure to agressive chemicals or solvents
		5	Exposure to abnormal moisture or water
		6	Exposure to non-electrical fire or burning
		8	Obstruction of ventilation by foreign object or material
		9	Normal deterioration from age
		10	Severe wind, rain, snow, sleet, or other weather conditions
		11	Protective relay improperly set
		12	Loss or deficiency of lubricant
		13	Loss or deficiency of oil or cooling medium
		14	Misoperation or testing error
		15	Exposure to dust or other contaminents
		99	Other

WHD

APPENDIX A (P. 7 of 7)

13

USER INSTRUCTIONS FOR CARD-TYPE 3

CARDS - TYPE 3

FAILURE															LOADS LOST*					% PRODUCTION LOST*	PLANT OUTAGE DURATION		SERVICE RESTORED*	CARD TYPE	CARD NO.
NUMBER	DATE MO.	DATE YR.	FOREWARNING*	DURATION NO. OF UNITS	DURATION UNITS*	REPAIR METHOD*	REPAIR URGENCY*	NO. SINCE LAST MAINTAINED*	DAMAGED PART*	TYPE*	RESPONSIBILITY*	INITIATING CAUSE*	CONTRIBUTING CAUSE*	CHARACTERISTIC*	COMPUTER	MOTOR	LIGHTING	SOLENOID	OTHER		NO. OF UNITS	UNITS*			
19	21	23	25	26	29	30	32	34	36	38	40	42	44	46	48	49	50	51	52	53	54	57	58	79	80
1																								3	1

COLUMN	NAME	CODE	DESCRIPTION
46	Failure Characteristic		Utility Power Supplies (Select code)
		1	Failure of single circuit (No redundant supply)
		2	Failure of one circuit of a double-circuit redundant supply
		3	Failure of both circuits of a double-circuit redundant supply
		4	Failure of all circuits of a three or more circuit redundant supply
		5	Partial failure of a three or more circuit redundant supply
			Transformers (Select code)
		6	Automatic removal by protective equipment
		7	Partial failure reducing capacity
		8	Manual removal
			Circuit Breakers (Select code)
		9	Failed to close when it should
		10	Failed while opening
		11	Opened when it shouldn't
		12	Damaged while successfully opening
		13	Damaged while closing
		14	Failed while operating (not while opening or closing)
			General (Select code for any other class)
		15	Failed (this applies to all classes)
		16	Failed during testing or maintenance
		17	Damage discovered during testing or maintenance
		20	Partial failure
		99	Other
	Loads Lost		What loads were lost because of failure (1=yes, 0=no, 9= not known) even though power is restored promptly
48	Computer		One or more computers or solid-state control devices operated incorrectly
49	Motor		One or more motors (contactor dropout)
50	Lighting		Lighting load
51	Solenoid		One or more solenoid -operated devices dropped out, such as a solenoid-operated fuel valve
52	Other		Lost other loads, describe in remarks
53	Percent Production Lost	0	None
		1	0-30 percent
		2	Above 30 percent

WHD

14

USER INSTRUCTIONS FOR CARD-TYPE 3

CARDS - TYPE 3

FAILURE															LOADS LOST*					% PRODUCTION LOST*	PLANT OUTAGE DURATION		SERVICE RESTORED*	CARD TYPE	CARD NO.
NUMBER	DATE		FOREWARNING*	DURATION		REPAIR METHOD*	REPAIR URGENCY*	NO. SINCE LAST MAINTAINED*	DAMAGED PART*	TYPE*	RESPONSIBILITY*	INITIATING CAUSE*	CONTRIBUTING CAUSE*	CHARACTERISTICS*	COMPUTER	MOTOR	LIGHTING	SOLENOID	OTHER		NO. OF UNITS	UNITS*			
	MO.	YR.		NO. OF UNITS	UNITS*																				
19	21	23	25	26	29	30	32	34	36	38	40	42	44	46	48	49	50	51	52	53	54	57	58	79	80
1																								3	1

COLUMN	NAME	CODE	DESCRIPTION
54	No of Units		Fill in number of time units selected in Col 57
57	Units		Select code for appropriate time unit that will give accurate results. For most cases select hours as unit.
		1	Days
		2	Hours
		3	Minutes
		4	Seconds
		5	Cycles
58	Service restored		Give method of restoring service to plant
		1	Primary selection -manual
		2	Primary selection -automatic
		3	Secondary selection -manual
		4	Secondary selection -automatic
		5	Network protector operation -automatic
		6	Repair of failed componenet
		7	Replacement of failed component with spare
		8	Utility restored service
		9	Other -explain in remarks

Discussion

Motors

The data in Tables 7 and 2 show that synchronous motors, 0–600 V, have a failure rate approximately 15 times lower than induction motors, 0–600 V. It is believed that the failure 0.0007 per year for synchronous motors, 0–600 V, is much too low and is in error. It is believed that synchronous and induction motors, 0–600 V, should have failure rates that are nearly the same.

Generators

The data in Tables 8 and 2 show that steam turbine driven generators have a failure rate almost 20 times lower than gas turbine driven generators. It is believed that the failure rate of 0.032 per year for steam turbine driven generators is too low; the failure rate should probably be several times higher than this value. The gas turbine data in Table 8 show that one plant in the petroleum industry had 54 failures in 5.5 unit-years; this compares with 3 failures in 83.9 unit-years for the other three plants that submitted data in the survey. It is believed that the overall failure rate of 0.638 per year for gas turbines is too high.

Open Wire

A clear definition was not given for "open wire" on the survey form (see Appendix A). It is believed that all of the respondents interpreted "open wire" to mean "bare or weatherproof conductors supported on insulators."

Cable

The data in Tables 13 and 2 show that cable above ground and aerial has a failure rate for 0–600 V that is ten times lower than 601–15 000 V. It is believed that the failure rate of 0.00141 per unit-year for 0–600 V above ground and aerial is too low.

There is a wide variation in the failure rate for cable, 601–15 000 V, based upon the application (in trays above ground, in conduit above ground, aerial cable, in duct or conduit below ground). This variation covers a range of 8 to 1. It is believed that the failure rate of 0.04918 per year is too high for cable, 601–15 000 V, in conduit above ground.

There is a wide variation in the cable failure rate shown in Table 14 (and Table 2) for the different types of insulation (601–15 000 V, all applications). These failure rates vary over a range of 5 to 1. The very low failure rate data for thermoplastic insulation and the high failure rate data for other insulation came primarily from the chemical industry.

Switchgear Bus

The failure rate in Table 10 (and Table 2) shows that insulated bus, 601–15 000 V, has a failure rate about three times higher than bare bus, above 600 V. It is believed that this is the opposite of what it should be. The data submitted by the chemical industry has caused this distortion; they had a very high failure rate for insulated bus (601–15 000 V) and a low failure rate for bare bus (above 600 V).

Electric Utility Power Supplies

The data for electric utility power supplies are shown in Tables 3 and 2. The failure rate is about the same for a single circuit and a double or triple circuit. This is evidently due to the predominance of the throwover mode of operation of multiple-circuit supplies. However, the actual downtime per failure is about three to nine times higher for a single circuit than for a double or triple circuit; the downtime depends on whether manual switchover or automatic switchover is used on a multiple-circuit system.

It appears that many respondents misinterpreted the "number of installed units" for double- or triple-circuit electric utility power supplies. What was desired was the number of separate and independent points of supply, but this was often interpreted to be the number of circuits in the utility supply system. Thus the tendency was to report two installed units for double-circuit supplies. It is believed that this error was made in almost every case. Therefore, *the Reliability Subcommittee changed the number of installed units for multiple-circuit utility supplies to 1 except in those cases where other evidence indicated the presence of more than one point of supply.* The sample size shown in Tables 3 and 2 reflects this change for double- or triple-circuit electric utility power supplies. Thus a double- or triple-circuit supply for one year is counted as one unit-year.

It also appears that a few respondents incorrectly interpreted failure duration on card type 3 for multiple-circuit electric utility supplies. What was desired was the period of time during which service was interrupted. However, in a few cases it appears that what was given was the time to repair one circuit of a multiple-circuit supply even though the supply interruption time is limited to the time required to throw over to the alternate supply circuit. The *Reliability Subcommittee changed the failure duration to the value given for plant outage duration in those cases in which such an error was believed to exist.* However, it is suspected that not all of these errors were corrected. The effect of this change was to reduce the actual hours of downtime per failure for multiple-circuit supplies. The majority of the multiple-circuit supply failures are due to loss of the normal feed, and the duration of the failure is limited to the time to switch to the alternate feed. The average outage duration in Tables 3 and 2 is shorter for automatic switching than for manual switching, as one would expect.

There were 25 recorded cases of simultaneous failure of all circuits in a double- or triple-circuit supply. This gives a failure rate of 0.119 failure per year for loss of all circuits at one time. Further details on this are given in Part 3 [13]. Thus a multiple-circuit electric utility power supply has a failure rate (loss of all circuits at one time) that is only about five times lower than the failure rate (0.537 failures per year) for a single-circuit supply and about six times lower than the all-inclusive failure rate of 0.643 failure per year. The ratio between all-inclusive failure rate and the failure rate for loss of all circuits at one time is not as large as one might suspect. Some of the reasons for this are the following.

1) Some portion of utility supply failures are due to failure of the bulk power system which feeds all the supply circuits.

2) At least some cases of loss of all circuits at one time occur when a forced outage of one circuit overlaps a scheduled or maintenance outage of the other circuit (typical utility industry data indicate that this type of overlapping outage is often more probable than overlapping forced outages).

3) The all-inclusive failure rate is, in effect, an average outage rate reflecting the performance of some throwover schemes and some normally closed breaker schemes. Thus, since throw-

over schemes are expected to have higher outage rates than normally closed breaker schemes, it follows that the computed all-inclusive outage rate is probably somewhat lower than the outage rate which would be computed for throwover schemes only. (Unfortunately we cannot compute the throwover scheme outage rate since we do not know which of the reported utility supplies are throwover schemes.)

Only point 3) reflects on the accuracy of the data; the other two points just reflect the facts of life.

A comparison of the all-inclusive failure rate (0.643 failures per year) with the failure rate for loss of all circuits at one time (0.119 failures per year) gives a rough idea of the degree of supply failure rate improvement possible by going from a throwover scheme to a scheme using normally closed circuit breakers.

References

[1] W. H. Dickinson, P. E. Gannon, C. R. Heising, A. D. Patton, and D. W. McWilliams, "Fundamentals of reliability techniques as applied to industrial power systems," in *Conf. Rec. 1971 IEEE Ind. Comm. Power Syst. Tech. Conf.* 71C18-IGA, pp. 10-31.
[2] C. R. Heising, "Reliability and availability comparison of common low-voltage industrial power distribution systems," *IEEE Trans. Ind. Gen. Appl.*, vol. IGA-6, pp. 416-424, Sept./Oct. 1970.
[3] W. H. Dickinson, "Economic evaluation of industrial power system reliability," *AIEE Trans. (Appl. Ind.)*, vol. 76, pp. 264-271, Nov. 1957.
[4] W. H. Dickinson, "Evaluation of alternative power distribution systems for refinery process units," *AIEE Trans. (Power Appl. Syst.)*, vol. 79, Apr. 1960.
[5] W. H. Dickinson, "Economic justification of petroleum industry automation and other alternatives by the revenue requirements method," *IEEE Trans. Ind. Gen. Appl.*, vol. IGA-1, pp. 39-50, Jan./Feb. 1965.
[6] D. P. Garver, F. E. Montmeat, and A. D. Patton, "Power systems reliability I—Measures of reliability and methods of calculation," *IEEE Trans. Power Appl Sys.*, vol. 83, pp. 727-737, July 1964.
[7] F. E. Montmeat, A. D. Patton, J. Zemkoski, and D. J. Cummin, "Power system reliability II—Applications and a computer program," *ibid.*, vol. PAS-84, pp. 636-643, July 1965.
[8] Z. G. Todd, "A probability method for transmission and distribution outage calculations," *IEEE Trans. Power App. Syst.*, vol. 83, pp. 695-701, July 1964.
[9] C. F. DeSieno, and L. L. Stine, "A probability method for determining the reliability of electric power systems," *IEEE Trans. Power App. Syst.*, vol. 83, pp. 174-181, Feb. 1964.
[10] "General principles for reliability analysis of nuclear power generating station protection systems," IEEE Publ. 352, ANSI N41.4, 1972.
[11] W. H. Dickinson, "Report on reliability of electric equipment in industrial plants," *AIEE Trans. (Appl. Ind.)*, vol. 81, pp. 132-151, July 1962.
[12] IEEE Committee Report, "Report on reliability survey of industrial plants, Part II: Cost of power outages, plant restart time, critical service loss duration time, and type of loads lost versus time of power outages," this issue, pp. 236-241.
[13] IEEE Committee Report, "Report on reliability survey of industrial plants; Part III: Causes and types of failures of electrical equipment, methods of repair, and urgency of repair," this issue, pp. 242-249.
[14] N. H. Roberts, *Mathematical Methods in Reliability Engineering.* New York: McGraw-Hill, 1964.
[15] I. Bazovsky, *Reliability Theory and Practice*. Englewood Cliffs, N.J.: Prentice-Hall, 1961.
[16] D. K. Lloyd and M. Lipow, *Reliability: Management, Methods, and Mathematics.* Englewood Cliffs, N.J.: Prentice-Hall, 1962.
[17] A. D. Patton, "Determination and analysis of data for reliability studies," *IEEE Trans. Power App. Syst.*, vol. PAS-87, pp. 84-100, Jan. 1968.

Report on Reliability Survey of Industrial Plants, Part II: Cost of Power Outages, Plant Restart Time, Critical Service Loss Duration Time, and Type of Loads Lost Versus Time of Power Outages

IEEE COMMITTEE REPORT

***Abstract*—An IEEE sponsored reliability survey of industrial plants was completed during 1972. This survey included the cost of power outages, plant restart time, critical service loss duration time, and type of loads lost versus power outage duration time. Survey results reflect data from 30 companies covering 68 plants in nine industries in the United States and Canada. This information is useful in the design of industrial power distribution systems.**

Introduction

KNOWLEDGE of the cost of power outages and of plant restart time is important information for use in the design of industrial power distribution systems. In addition it is also desirable to know the critical service loss duration time and the type of loads lost versus the time of power outage.

During 1972 the Reliability Subcommittee of the IEEE Industrial and Commercial Power Systems Committee completed a reliability survey of industrial plants. This is the second part, which reports results from the survey. Included in this paper are the following results:

1) cost of power outages to industrial plants in the United States and Canada (dollars per kilowatt interrupted plus dollars per kilowatthour of undelivered energy);
2) plant restart time after a failure that has caused complete plant shutdown;
3) critical service loss duration time, that is, the maximum length of power failure that will not stop plant production;
4) type of loads lost versus the time of power outage (this includes computer, motor, lighting, and solenoid loads, and gives plant outage duration times resulting from these failures).

Paper TOD-73-158, approved by the Industrial and Commercial Power Systems Committee of the IEEE Industry Applications Society for presentation at the 1973 Industrial and Commercial Power Systems Technical Conference, Atlanta, Ga., May 13-16. Manuscript released for publication November 5, 1973.
Members of the Reliability Subcommittee of the IEEE Industrial and Commercial Power Systems Committee are W. H. Dickinson, *Chairman*, P. E. Gannon, M. D. Harris, C. R. Heising, D. W. McWilliams, R. W. Parision, A. D. Patton, and W. J. Pearce.

Survey Form

The survey form used is shown in Appendix A of Part 1 [1]. The information on the cost of power outages came from card type 1, columns 13, 20, and 25. Card type 1 also contained plant restart time (column 31) and critical service loss duration (columns 33 and 36).

The data on type of loads lost came from card type 3, columns 48, 49, 50, 51, and 52. The data on time of power outage came from columns 26 and 29 of card type 3; these data are actually the outage duration time after a failure of the electric utility power supply or a failure of electrical equipment in the power distribution system.

Response to Survey

A total of 30 companies responded to the survey questionnaire reporting data on 68 plants from nine industries in the United States and Canada. Every response did not supply all the information requested on every question. Tables 22-29

give data on how many plants provided answers to the various questions.

Statistical Analysis

The results were compiled for the United States and Canada. Data from one foreign plant are also included separately.

Survey Results

Cost of Power Outages

Each plant was asked to report data on the cost of power outages as follows:

1) Dollars per failure, i.e., extra expense incurred because of a failure only (not including plant downtime) such as for damaged equipment, spoiled product, extra maintenance, or extra repair costs.

2) Dollars per hour of downtime, i.e., value of lost production in dollars per hour of plant downtime only. This is the estimated revenues (sales price) of product not made, less expenses saved in labor, material, utilities, etc. If this varies with the duration of the plant downtime, an average value per hour was to be given.

3) Maximum electric power demand when the plant is operating at its rated or design capacity in kilowatts.

This made it possible to calculate an estimate of the cost of power outages in terms of the dollars per kilowatts interrupted plus the dollars per kilowatthours of undelivered energy. The average cost of power outages from the survey is given in Table 20.

Of the 41 plants that reported outage cost data in the survey, 31 had a maximum demand greater than 1000 kW and 10 had a maximum demand less than 1000 kW. Cost data for plants with maximum demands less than 1000 kW are not considered particularly reliable due to the small number of such plants represented in the data.

There is a wide spread in the cost of power outages. Consequently few plants with high outage costs can have a significant effect on the overall average cost. In such cases the median cost of power outages may be more representative than the average cost. The median cost is such that half of the plants have a cost greater than this value and half have less. Table 21 shows the median power outage costs. Additional details on the cost of power outages are given in Tables 22-27. These additional details include: 1) number of plants reporting the outage cost per failure and the outage cost per hour of downtime, 2) minimum plant cost, 3) maximum plant cost, 4) costs for various industries.

Tables 22, 24, and 26 give the cost of outage per failure per kilowatt maximum demand. Tables 23, 25, and 27 give the cost of a sustained outage per hour down per kilowatt maximum demand.

Plant Restart Time

Each plant was asked to report data on the time required to get the plant back into operation after service is restored following a failure that has caused a complete plant shutdown. A total of 43 plants reported these data. The average plant

TABLE 20 - AVERAGE COST OF POWER OUTAGES FOR INDUSTRIAL PLANTS IN THE UNITED STATES OF AMERICA AND CANADA

All Plants	\$1.89 per kW + \$2.68 per kWh
Plants > 1000 kW Max. Demand	\$1.05 per kW + \$0.94 per kWh
Plants < 1000 kW Max. Demand	\$4.59 per kW + \$8.11 per kWh

TABLE 21 - MEDIAN COST OF POWER OUTAGES FOR INDUSTRIAL PLANTS IN THE UNITED STATES OF AMERICA AND CANADA

All plants	\$0.69 per kW + \$0.83 per kWh
Plants > 1000 kW Max. Demand	\$0.32 per kW + \$0.36 per kWh
Plants < 1000 kW Max. Demand	\$3.68 per kW + \$4.42 per kWh

restart time was 17 h. The median was 4 h. Additional details are given in Table 28.

Critical Service Loss Duration Time

One of the most commonly asked questions is, What is a power failure? In particular, How long can power be lost without causing a complete plant shutdown? Each plant was asked to report data giving the maximum length of power failure that will not stop plant production. This time is typically in the range of cycles to minutes and is called "critical service loss duration time."

A total of 55 plants reported data on critical service loss duration time. The median value was 10 s, that is, half of the plants were greater than this value and half were less. Additional details are given in Table 29.

Loads Lost Versus Time of Power Outage

Each plant was asked, What loads were lost because of failure even though power was restored promptly? Five types of loads were included in the survey:

1) *computer:* one or more computers or solid-state control devices operated incorrectly;
2) *motor:* one or more motors (contactor dropout);
3) *lighting:* lighting load;
4) *solenoid:* one or more solenoid-operated devices dropped out, such as a solenoid-operated fuel valve;
5) *other:* lost other loads, to be described in remarks.

A very short outage duration time after an equipment failure (including electric utility power supply) might not result in a loss of load. Table 30 shows how short power outage duration times after an equipment failure affected the loads lost. The average plant outage duration resulting from these failures is also given in Table 30.

Discussion of Results

Cost of Power Outages (Tables 20–27)

1) There is a wide spread in the cost of power outages (per kilowatt and per kilowatthour) of industrial plants. Even within a given industry, such as chemical, there is a wide spread in the cost of power outages (per kilowatt and per kilowatthour) for different plants.

2) Plants with a maximum demand of less than 1000 kW have a much higher cost of power outages (per kilowatt and per kilowatthour) than plants with a maximum demand of greater than 1000 kW. This indicates that small industrial plants have a higher cost of power outages (per kilowatt and per kilowatthour) than large industrial plants. It is suspected that this may be because the small industrial plants have more employees per kilowatt (and per kilowatthour). It is also possible that high-consumption industries tend to have a lot of electrochemical or heating processes, and these tend to have low outage costs; for example, heat not supplied now can be supplied later, providing the outage is not too long.

3) It is suggested that the "all-industry" data for the 41 and 42 plants should be compiled to show 25 percent and 75 percent in addition to the minimum median and maximum values already tabulated (Tables 22 and 23).

4) It is suggested that future surveys also include the cost of power outages (per kilowatt and per kilowatthour) of commercial buildings.

TABLE 22 - PLANT OUTAGE COST PER FAILURE PER kW OF MAXIMUM DEMAND - ALL PLANTS ($ per kW)

Industry	Number of Plants Reporting	Minimum	Median	Maximum	Average
All Industry - USA & Canada	42	.002	.69	10.00	1.89
Auto......................	0	-	-	-	-
Cement....................	0	-	-	-	-
Chemical..................	11	.02	.22	3.33	.75
Metal.....................	2	.18	2.42	4.67	2.42
Mining....................	0	-	-	-	-
Petroleum.................	5	.002	.07	.31	.12
Pulp and Paper............	1	.33	.33	.33	.33
Rubber and Plastics........	2	.28	.50	.71	.50
Textile...................	2	.07	1.00	1.92	1.00
Other Light Manufacturing..	6	.09	1.10	2.80	1.22
Other Heavy Manufacturing..	8	1.67	3.85	10.00	5.11
Other.....................	5	.25	.94	7.50	2.86
Foreign...................	1	.33	.33	.33	.33

TABLE 23 - PLANT OUTAGE COST PER HR. DOWNTIME PER kW OF MAXIMUM DEMAND - ALL PLANTS ($ per kWh)

Industry	Number of Plants Reporting	Minimum	Median	Maximum	Average
All Industry - USA & Canada	41	.0009	.83	27.00	2.68
Auto......................	0	-	-	-	-
Cement....................	0	-	-	-	-
Chemical..................	12	.0009	.14	2.11	.33
Metal.....................	2	.55	.94	1.33	.94
Mining....................	0	-	-	-	-
Petroleum.................	2	.04	1.24	2.43	1.24
Pulp and Paper............	1	.07	.07	.07	.07
Rubber and Plastics........	3	.28	.36	1.33	.66
Textile...................	1	.24	.24	.24	.24
Other Light Manufacturing..	6	.33	.79	2.00	.91
Other Heavy Manufacturing..	8	.93	6.35	27.00	9.73
Other.....................	6	.75	2.50	5.77	2.69
Foreign...................	1	.07	.07	.07	.07

TABLE 24 - PLANT OUTAGE COST PER FAILURE PER kW OF MAXIMUM DEMAND - PLANTS MORE THAN 1,000 kW MAX. DEMAND ($ per kW)

Industry	Number of Plants Reporting	Minimum	Median	Maximum	Average
All Industry - USA & Canada	32	.002	.32	7.50	1.05
Auto......................	0	-	-	-	-
Cement....................	0	-	-	-	-
Chemical..................	11	.02	.22	3.33	.75
Metal.....................	1	.18	.18	.18	.18
Mining....................	0	-	-	-	-
Petroleum.................	5	.002	.07	.31	.12
Pulp and Paper............	1	.33	.33	.33	.33
Rubber and Plastics.......	2	.28	.50	.71	.50
Textile...................	2	.07	1.00	1.92	1.00
Other Light Manufacturing...	4	.09	1.10	2.80	1.27
Other Heavy Manufacturing...	1	1.87	1.87	1.87	1.87
Other.....................	5	.25	.94	7.50	2.86
Foreign...................	1	.33	.33	.33	.33

TABLE 25 - PLANT OUTAGE COST PER HR. DOWNTIME PER kW OF MAXIMUM DEMAND - PLANTS MORE THAN 1,000 kW MAX. DEMAND ($ per kWh)

Industry	Number of Plants Reporting	Minimum	Median	Maximum	Average
All Industry - USA & Canada	31	.0009	.36	5.77	.94
Auto......................	0	-	-	-	-
Cement....................	0	-	-	-	-
Chemical..................	12	.0009	.14	2.11	.33
Metal.....................	1	.55	.55	.55	.55
Mining....................	0	-	-	-	-
Petroleum.................	2	.04	1.24	2.43	1.24
Pulp and Paper............	1	.07	.07	.07	.07
Rubber and Plastics.......	3	.28	.36	1.33	.66
Textile...................	1	.24	.24	.24	.24
Other Light Manufacturing..	4	.33	.54	1.20	.65
Other Heavy Manufacturing..	1	.93	.93	.93	.93
Other.....................	6	.75	2.50	5.77	2.69
Foreign...................	1	.07	.07	.07	.07

TABLE 26 - PLANT OUTAGE COST PER FAILURE PER kW OF MAXIMUM DEMAND - PLANTS LESS THAN 1,000 kW MAX. DEMAND ($ per kW)

Industry	Number of Plants Reporting	Minimum	Median	Maximum	Average
All Industry - USA & Canada	10	.50	3.68	10.00	4.59
Auto......................	0	-	-	-	-
Cement....................	0	-	-	-	-
Chemical..................	0	-	-	-	-
Metal.....................	1	4.67	4.67	4.67	4.67
Mining....................	0	-	-	-	-
Petroleum.................	0	-	-	-	-
Pulp and Paper............	0	-	-	-	-
Rubber and Plastics.......	0	-	-	-	-
Textile...................	0	-	-	-	-
Other Light Manufacturing...	2	.50	1.11	1.72	1.11
Other Heavy Manufacturing...	7	1.67	5.00	10.00	5.57
Other.....................	0	-	-	-	-
Foreign...................	0	-	-	-	-

TABLE 27 - PLANT OUTAGE COST PER HR. DOWNTIME PER kW OF MAXIMUM DEMAND - PLANTS LESS THAN 1,000 kW MAX. DEMAND ($ per kWh)

Industry	Number of Plants Reporting	Minimum	Median	Maximum	Average
All Industry - USA & Canada	10	.86	4.42	27.00	8.11
Auto......................	0	-	-	-	-
Cement....................	0	-	-	-	-
Chemical..................	0	-	-	-	-
Metal.....................	1	1.33	1.33	1.33	1.33
Mining....................	0	-	-	-	-
Petroleum.................	0	-	-	-	-
Pulp and Paper............	0	-	-	-	-
Rubber and Plastics.......	0	-	-	-	-
Textile...................	0	-	-	-	-
Other Light Manufacturing..	2	.86	1.43	2.00	1.43
Other Heavy Manufacturing..	7	3.33	7.69	27.00	11.00
Other.....................	0	-	-	-	-
Foreign...................	0	-	-	-	-

TABLE 28 - PLANT RESTART TIME (After Service is Restored Following a Failure that has Caused Complete Plant Shutdown)

Industry	Number of Plants Reporting	Average (Hours)	Median (Hours)
All Industry - USA & Canada..	43	17.4	4.0
Auto........................	0	-	-
Cement......................	0	-	-
Chemical....................	19	20.7	20
Metal.......................	1	4	4
Mining......................	0	-	-
Petroleum...................	3	37.3	24
Pulp and Paper..............	1	10	10
Rubber & Plastics...........	3	2.33	2
Textile.....................	3	58.3	72
Other Light Manufacturing....	7	2.14	2
Other Heavy Manufacturing....	1	2	2
Other.......................	5	2.6	1
Foreign.....................	1	48	48

TABLE 29 - CRITICAL SERVICE LOSS DURATION (Maximum Length of Power Failure that Will Not Stop Plant Production)

Industry	Number of Plants Reporting	Average	Median
All Industry - USA & Canada....	55	12.6 min.	10.0 sec.
Auto..........................	0	-	-
Cement........................	0	-	-
Chemical......................	20	4.56 min.	1.25 sec.
Metal.........................	2	15.0 min.	15.0 min.
Mining........................	0	-	-
Petroleum.....................	1	1.0 sec.	1.0 sec.
Pulp and Paper................	1	10.0 cycles	10.0 cycles
Rubber & Plastics.............	3	30.0 sec.	20.0 sec.
Textile.......................	3	3.34 min.	30.0 cycles
Other Light Manufacturing......	7	10.3 min.	10.0 sec.
Other Heavy Manufacturing......	10	47 min.	45 min.
Other.........................	8	1.9 min.	20.0 cycles
Foreign.......................	1	15.0 cycles	15.0 cycles

TABLE 30 - LOADS LOST VERSUS TIME OF POWER OUTAGE
(Tabulation of the Percentage of Equipment Failures for Which the Designated Load was Lost and Average Plant Outage Duration Resulting from these Failures)

	For Equipment Failures 1 Cycle or less in Duration			For Equipment Failures Between 1 and 10 Cycles in Duration			For Equipment Failures 10 Cycles or More in Duration		
Type of Load	Yes	No	Not Known	Yes	No	Not Known	Yes	No	Not Known
Computer	0%	0%	0%	4%	96%	0%	9%	91%	0%
Motor	0%	0%	0%	33%	67%	0%	67%	33%	0%
Lighting	0%	0%	0%	22%	78%	0%	38%	61%	2%
Solenoid	0%	0%	0%	22%	74%	4%	25%	66%	9%
Other	0%	0%	0%	7%	15%	78%	25%	62%	13%
Average Plant Outage Duration	0.0 Hours			1.39 Hours			22.6 Hours		

Only non-zero data was used in computing the average plant outage duration

5) Additional information on the cost of power outages in Sweden, Norway, and the United States is contained in [2].

Plant Restart Time (Table 28)

The textile, petroleum, and chemical industries have a much longer plant restart time than the other industries included in the survey.

Critical Service Loss Duration (Table 29)

1) There is a wide spread in critical service loss duration time for the 55 plants in the survey.

2) It is suggested that the data from the 55 plants should be compiled to show several percentiles (10, 25, 75, and 90 percent) in addition to the median value already tabulated.

Loads Lost Versus Time of Power Outage (Table 30)

1) An outage between 1 to 10 cycles resulted in 33 percent of the plants losing motor loads and 22 percent losing a solenoid and only 4 percent losing a computer load. An outage greater than 10 cycles resulted in 67 percent of the plants losing motor loads and 25 percent losing a solenoid and only 9 percent losing a computer load; many plants must not have had computer loads to give such a low value. In fact, many plants must not have had motor loads or solenoid loads either. The important parameter to look at is the change in these percentages from 0 to the maximum value as the length of power outage time is increased.

2) It is suggested that loss of load data be compiled for the following additional categories of outage duration time:

a) 10 to 15 cycles,
b) 15+ to 30 cycles,
c) 0.5 + to 2.0 s,
d) 2.0+ to 4.0 s,
e) greater than 4.0 s.

The average plant outage duration should also be determined for these categories.

References

[1] IEEE Committee Report, "Report on reliability survey of industrial plants; Part I: Reliability of electrical equipment," this issue, pp. 213-235.
[2] R. B. Shipley, A. D. Patton, and J. S. Denison "Power reliability cost vs worth," *IEEE Trans. Power App. Syst.*, vol. PAS-91, pp. 2204-2212, Sept./Oct. 1972.

Report on Reliability Survey of Industrial Plants, Part III: Causes and Types of Failures of Electrical Equipment, the Methods of Repair, and the Urgency of Repair

IEEE COMMITTEE REPORT

***Abstract*—An IEEE sponsored reliability survey of industrial plants was completed during 1972. This included the causes and types of failures of electrical equipment, the methods of repair, and the urgency of repair. The results are reported from the survey of 30 companies covering 68 plants in nine industries in the United States and Canada. This information is useful in the design of industrial power distribution systems.**

Introduction

A KNOWLEDGE of the causes and types of failures of electrical equipment is useful in the design of industrial power distribution systems. In addition it is also useful to know the failure repair method, whether or not the repair was urgent, and how long it had been since the previous maintenance had been performed. During 1972 the Reliability Subcommittee of the IEEE Industrial and Commercial Power Systems Committee completed a reliability survey of industrial plants. This is the third paper reporting results from the survey. Included in this paper are the results for 14 main classes of electrical equipment on

1) failure repair method;
2) failure repair urgency;
3) failure, months since maintained;
4) failure, damaged part;
5) failure type;
6) suspected failure responsibility;
7) failure initiating cause;
8) failure contributing cause;
9) failure characteristic.

The failure repair method includes either the repair of the failed component or the replacement of the failed component with a spare. This can have a significant effect on the average downtime per failure, and thus is an important factor in reliability and availability calculations.

Paper TOD-73-158, approved by the Industrial and Commercial Power Systems Committee of the IEEE Industry Applications Society for presentation at the 1973 Industrial and Commercial Power Systems Technical Conference, Atlanta, Ga., May 13-16. Manuscript released for publication November 5, 1973.

Members of the Reliability Subcommittee of the IEEE Industrial and Commercial Power Systems Committee are W. H. Dickinson, *Chairman*, P. E. Gannon, M. D. Harris, C. R. Heising, D. W. McWilliams, R. W. Parisian, A. D. Patton, and W. J. Pearce.

The failure repair urgency also has a significant effect on the average downtime per failure and thus is an important factor in reliability and availability calculations.

A preventive maintenance program can have an effect on the failure rate of electrical equipment. Thus a knowledge of whether or not maintenance has been performed recently prior to the failure is a significant factor in helping to determine whether or not the maintenance program is adequate.

The damaged part from a failure is of interest. In addition, a knowledge is also desirable of the type of failure, initiating cause, contributing cause, and suspected responsibility. This information is useful for correcting deficiencies in electrical equipment and electrical systems.

The failure characteristic can be defined as the effect that the failure has on the electrical system. Thus this information is very important.

Survey Form

The survey form used is shown in Appendix A of Part 1 [1]. All of the information reported on in this paper came from card type 3, columns 30-46. The definitions of *failure* and *repair time* are given in Part 1 [1].

Response to Survey

A total of 30 companies responded to the survey questionnaire, reporting data on 68 plants from nine industries in the United States and Canada. Every failure report on card type 3 did not have filled in all the information called for in columns 30-46. Tables 31 and 32 give the data for each main equipment class on how many failures had the information called for in columns 30-46. Each main equipment class contains 18 or more failures; this is believed to be an adequate statistical sample size.

Statistical Analysis

The results were compiled for 14 main equipment classes. The number of failures were tabulated for each category of each column (30-46, card type 3). This was then divided by the total failures in each column so as to give the percentage for each category for each column (for each main equipment class).

Survey Results

The results are tabulated for the 14 main equipment classes in Tables 33-41. Each table represents one column (of 30-46, card type 3).

Summary of Conclusions

Transformers

In the cases reported, there were approximately an equal number of incidences of repairing the failed transformer and replacing it with a spare. The repair urgency slightly favored a round-the-clock repair over the regular work-day schedule. Inadequate preventive maintenance did not seem to have much influence on the reported failures since no preventive maintenance was reported on only 5 percent of the failures; 11 percent of the failures were blamed on inadequate maintenance. Damaged insulation both in the windings and bushings accounted for the majority of the transformer damage, with the majority of failures being flashovers involving ground. 24 percent of the reported cases considered normal deterioration from age as the contributing cause of the failure, yet 39 percent reported that they felt the manufacturer was primarily responsible. Transient overvoltages, from lightning or switching surges, and other insulation breakdown account for 41 percent of the reported failures. In 90 percent of the reported cases the transformers were removed from the system by automatic protective devices; only 7 percent had manual removal.

Circuit Breakers

About the same number of circuit breakers were repaired in place as were replaced by spares. The relative importance of circuit breakers was indicated by 73 percent of the survey respondents making repairs on a round-the-clock basis. The bulk of the reported failures involved flashovers to ground with damage primarily to the protective device components and the device insulation. Transient overvoltages, insulation breakdowns, and protective device malfunctions were considered a major initiating cause with normal deterioration from age and misoperation or testing errors considered as contributing causes. However, 33 percent of the respondents could not classify the initiating cause into any of the survey classes, and 55 percent could not classify the contributing cause into any of the survey classes. In addition, 36 percent of the suspected causes of failure were blamed on "other." 42 percent of the reported failures involved circuit breakers opening when they should not; it is possible that several of these failures were external to the circuit breaker and of unknown cause and were blamed on the circuit breaker. 32 percent of the reported failures involved circuit breakers that failed during a load-carrying condition.

23 percent of the failures were blamed on the manufacturer and another 23 percent on inadequate maintenance, but 36 percent were blamed on "other." Inadequate preventive maintenance (PM) could be a factor of some significance since no PM was reported on 16 percent of the failures.

Motor Starters

Of the reported motor starter failures, about two thirds were repaired by replacing the starter with a spare and two thirds were repaired on a round-the-clock basis. About half of the cases reported indicate that the damage was other than the classes listed in the survey, primarily resulting from flashovers or electrical defects. 64 percent felt that a malfunction of a protective relay control device initiated the failure with 40 percent of the respondents reporting that normal deterioration from age was a contributing cause. Over half of the respondents felt that improper application was primarily responsible for the failure. In the cases reported 36 percent had been discovered during testing or maintenance, and 20 percent were only partial failures. Lack of preventive maintenance was not a big problem. Those starters that had been maintained less than 12 months prior to the failure accounted for 67 percent of the cases reported.

Motors

Of the reported motor failures, about three quarters were repaired versus about one fourth being replaced by a spare. About three quarters were repaired on a regular work-day basis. The types of failures varied from flashovers to electrical defects, to mechanical defects, with winding insulation and bearings sustaining the majority of the damage. Insulation breakdown, overheating, and mechanical seizing were blamed as the primary initiating causes with normal deterioration from age, loss or deficiency of lubricant, exposure to abnormal moisture, and exposure to aggressive chemicals ranking high on the list of contributing causes. 30 percent of the failures were discovered during testing or maintenance, which probably resulted in less actual damage in those cases. Inadequate maintenance, improper application, and defective equipment were listed as having primary responsibility. However, over half of the respondents could not assign responsibility into one of the survey classes. The motors that had been maintained between 12 and 24 months prior to the failure accounted for 57 percent of the reported cases with less than 12 months and more than 24 months accounting for 22 percent and 19 percent, respectively. No preventive maintenance accounted for only 2 percent, yet this does not correlate well with inadequate maintenance being listed as having primary responsibility in 17 percent of the reported cases.

Generators

Of the reported generator failures 84 percent were repaired in place. About the same number were repaired on a round-the-clock basis as were repaired on a regular work-day basis. 69 percent of the respondents reported damage other than the survey classes with electrical auxiliaries, winding insulation, and moving parts sustaining some damage. Mechanical breaking, transient overvoltages, and about half unclassified items were considered the primary initiating causes with normal deterioration from age and persistent overloading considered contributing causes. Responsibility was spread between inadequate maintenance and defective components with about half of the respondents unable to place primary responsibility into any of the survey classes. Infrequent or no preventive maintenance were not involved in any of the reported cases, a point that does not correlate with the fact that some of the respondents felt inadequate maintenance was the primary responsibility.

Disconnect Switches

Of the reported disconnect switch failures, 70 percent were repaired by replacement with a spare, with work in 80 percent of the cases being performed on a regular work-day schedule. Electrical defects, mechanical defects, and flashovers to ground resulted in damage to mechanical components and insulation. Some form of mechanical breaking or contact from foreign

TABLE 31 - NUMBER OF FAILURES FOR ELECTRIC UTILITY POWER SUPPLIES THAT CONTAINED THE INFORMATION CALLED FOR IN COLUMNS 30-46, CARD - TYPE 3

Card Type 3 Column	Title	Number of Failures
30	Failure Repair Method.............	28
32	Failure Repair Urgency............	35
34	Failure, Months Since Maintained..	25
36	Failure, Damaged Part.............	39
38	Failure Type......................	49
40	Suspected Failure Responsibility..	43
42	Failure Initiating Cause..........	53
44	Failure Contributing Cause........	53
46	Failure Characteristic............	145

TABLE 32 - NUMBER OF FAILURES FOR EACH MAIN EQUIPMENT CLASS THAT CONTAINED THE INFORMATION CALLED FOR IN COLUMNS 30-46, CARD-TYPE 3

Main Equipment Class	Maximum	Minimum	Avg.
Transformers	101	97	100
Circuit Breakers	176	161	171
Motor Starters	88	88	88
Motors	561(col.36)	493(col.40)	517
Generators	83(col.36)	31(all other)	37
Disconnect Switches	101	100	101
Swgr. Bus-Insulated	20	20	20
Swgr. Bus-Bare	24	20	23
Bus Duct	20	18	20
Open Wire	109	104	108
Cable	223	211	218
Cable Joints	45	44	45
Cable Terminations	51	47	50

sources accounted for about half of the initiating causes, with exposure to dust and contaminants and a large number of unclassified items considered contributing causes. Inadequate operating procedures, inadequate maintenance, and defective components were considered primarily responsible, which seems to correlate with over 66 percent of the reported cases not having any preventive maintenance and 21 percent not having any preventive maintenance 24 months prior to the failure.

Switchgear Bus, Bare

Of the reported uninsulated switchgear bus failures, about two thirds were repaired in place, with a little more than half of them being repaired on a round-the-clock basis. 79 percent of the respondents report some form of insulation damage all resulting from flashovers either to ground (79 percent) or between phases (21 percent). Mechanical failure, shorting by metal objects, and insulation breakdown were the predominant initiating causes with exposure to abnormal moisture, exposure to dust, exposure to aggressive chemicals, and normal deterioration due to age listed as contributing causes. Interestingly, 15 percent of the respondents listed misoperation or testing errors as a contributing cause. 39 percent felt that an outside agency was responsible for the failure, while 22 percent blamed inadequate maintenance.

Switchgear Bus, Insulated

Of the reported insulated switchgear bus failures, essentially all were repaired in place with over two thirds of the repairs being completed on a round-the-clock basis. 90 percent of the respondents reported insulation damage resulting primarily from flashovers to ground and between phases. Insulation breakdown was considered to have initiated the failure in about half of the cases, with exposure to contaminants, moisture, severe weather, and normal deterioration from age being considered as contributing factors. Improper application (45 percent) and inadequate maintenance (35 percent) were held responsible for the failures.

Bus Duct

Of the reported bus duct failures, 65 percent were repaired in place with the majority of them being repaired on a round-the-clock basis. 90 percent of the respondents reported some form of damaged insulation resulting from a flashover to ground. Mechanical failure, insulation breakdown, and overheating were blamed as initiating factors, with normal deterioration due to age being listed as a contributing factor in half of the cases. Responsibility for the reported failures varied from defective components (26 percent), improper application (16 percent), to inadequate maintenance (16 percent).

Open Wire

Of the reported open-wire failures, 70 percent were repaired in place with a little over half involving a round the clock effort. About half of the failures involved flashovers either to ground or between phases and about 25 percent involved other electrical defects. In the reported failures, transient overvoltages, overheating, or shorting by metal objects were considered the most significant initiating causes, with severe weather and exposure to aggressive chemicals being the predominant contributing causes. 81 percent of the respondents indicated that no preventive maintenance had been performed in over two years, which supports the fact that over a third of them blamed inadequate maintenance as being responsible.

Cables

The relative importance of primary cable was again indicated by about two thirds of the reported cases making repairs on a round-the-clock basis. There were a few more reported cases where repairs to cables were made by complete replacement rather than by in-place repairs. About three quarters of the failures involved flashovers to ground, resulting in insulation damage.

TABLE 33 - FAILURE REPAIR METHOD
TABLE 34 - FAILURE REPAIR URGENCY

ELECTRIC UTILITY POWER SUPPLIES	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS - INSULATED	SWITCHGEAR BUS - BARE	BUS DUCT	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS	Table, Title, Category
%	%	%	%	%	%	%	%	%	%	%	%	%	%	TABLE 33 - FAILURE REPAIR METHOD (Col. 30)
50	47	51	33	78	84	30	95	71	65	70	47	87	60	1. Repair of failed component in place or sent out for repair
46	53	49	67	22	16	70	5	29	35	9	53	13	34	2. Repair by replacement of failed component with spare
4	0	0	0	0	0	0	0	0	0	21	0	0	6	99. Other
														TABLE 34 - FAILURE REPAIR URGENCY (Col. 32)
91	51	73	66	23	48	20	70	58	80	55	66	56	53	1. Requiring round-the-clock all out efforts
9	45	22	34	74	52	80	25	33	15	26	28	22	31	2. Requiring repair work only during regular workday, perhaps with some overtime
0	4	5	0	2	0	0	5	8	5	0	6	22	16	3. Requiring repair work on a non-priority basis
0	0	0	0	0	0	0	0	0	0	19	0	0	0	99. Other

TABLE 35 - FAILURE, MONTHS SINCE MAINTAINED
TABLE 36 - FAILURE, DAMAGED PART

ELECTRIC UTILITY POWER SUPPLIES	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS-INSULATED	SWITCHGEAR BUS-BARE	BUS DUCT	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS	Table, Title, Category
														TABLE 35 - FAILURE, MONTHS SINCE MAINTAINED (Col. 34)
56	34	18	67	22	58	8	10	35	25	1	11	18	12	1. Less than 12 months ago
40	38	60	17	57	42	5	35	30	45	8	13	20	12	2. 12-24 months ago
4	22	5	16	19	0	21	55	13	10	81	10	2	36	3. Over 24 months ago
0	5	16	0	2	0	66	0	22	20	9	66	60	40	4. No preventive maintenance
0	0	0	0	0	0	0	0	0	0	0	0	0	0	99. Other
														TABLE 36 - FAILURE, DAMAGED PART (Col. 36)
0	68	0	5	50	7	0	0	0	15	0	5	0	0	1. Insulation - winding
8	13	2	0	0	0	1	5	8	10	1	0	0	12	2. Insulation - bushing
10	3	19	10	3	0	14	90	71	65	6	84	91	75	3. Insulation - other
0	0	1	0	29	2	0	0	0	0	0	3	0	0	4. Mechanical - bearings
3	0	11	16	3	7	9	0	0	0	0	0	0	0	5. Mechanical - other moving parts
15	1	6	2	1	4	30	0	0	0	4	1	0	4	6. Mechanical - other
10	3	6	13	3	10	8	5	0	0	3	1	0	0	7. Other electrical - auxiliary device
10	1	28	2	0	1	1	0	0	0	3	1	0	0	8. Other electrical - protective device
0	7	1	0	0	0	0	0	0	0	0	0	0	0	9. Tap changer - no load type
0	1	0	0	0	0	0	0	0	0	0	0	0	0	10. Tap changer - load type
44	3	26	52	11	69	38	0	21	10	84	6	9	10	99. Other

TABLE 37 - FAILURE TYPE

ELECTRIC UTILITY POWER SUPPLIES	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS-INSULATED	SWITCHGEAR BUS-BARE	BUS DUCT	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS	Table, Title, Category
														TABLE 37 - FAILURE TYPE (col. 38)
43	58	33	14	28	19	15	65	79	70	34	73	70	55	1. Flashover or arcing involving ground
4	13	10	20	4	3	4	35	21	30	23	1	9	4	2. All other flashover or arcing
14	12	19	55	32	29	47	0	0	0	25	7	20	37	3. Other electrical defect
8	10	11	11	31	32	14	0	0	0	6	5	0	4	4. Mechanical defect
31	7	27	0	6	16	21	0	0	0	12	14	0	0	99. Other

TABLE 38 - SUSPECTED FAILURE RESPONSIBILITY

ELECTRIC UTILITY POWER SUPPLIES	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS - INSULATED	SWITCHGEAR BUS - BARE	BUS DUCT	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS	Table, Title, Category
%	%	%	%	%	%	%	%	%	%	%	%	%	%	TABLE 38 - SUSPECTED FAILURE RESPONSIBILITY
8	39	23	18	15	19	29	5	9	26	0	16	0	0	1. Manufacturer-defective Component
0	0	0	0	0	0	0	0	0	0	0	0	0	0	2. Transportation to Site - defective handling
0	2	4	51	9	0	6	45	4	16	2	8	0	18	3. Application Engineering - improper application
0	3	3	0	1	3	4	10	17	5	9	14	50	39	4. Inadequate installation and testing prior to start-up
0	11	23	8	17	19	13	35	22	16	30	10	18	22	5. Inadequate maintenance
6	9	6	3	4	3	40	0	0	0	2	3	0	0	6 Inadequate operating procedures
17	2	5	0	0	0	1	0	22	5	5	4	5	0	7. Outside agency - personnel
32	4	1	0	1	6	0	0	17	0	21	6	2	8	8. Outside agency - other
38	30	36	19	53	48	8	5	9	32	31	38	25	14	99. Other

TABLE 39 - FAILURE INITIATING CAUSE

ELECTRIC UTILITY POWER SUPPLIES	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS – INSULATED	SWITCHGEAR BUS – BARE	BUS DUCT	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS	Table, Title, Category
														TABLE 39 - FAILURE INITIATING CAUSE(Col. 42)
33	23	13	1	6	10	4	5	5	0	26	26	11	12	1. Transient overvoltage disturbance (lightning, switching surges, arcing ground fault in ungrounded system)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	2. Overvoltage
0	11	3	1	26	3	4	0	5	30	21	1	0	2	3. Overheating
5	18	18	8	30	3	5	50	18	20	8	29	40	51	4. Other insulation breakdown
7	17	13	8	4	29	17	10	23	45	7	24	31	24	21. Mechanical breaking, cracking, loosening, abrading or deforming of static or structural parts
2	0	5	6	20	3	2	0	0	0	0	0	0	0	22. Mechanical burnout, friction, or seizing of moving parts.
14	1	1	0	3	3	20	0	0	0	10	7	0	4	23. Mechanically caused damage from foreign source (digging, vehicular, accident,etc.)
12	1	2	5	0	0	0	0	23	5	14	2	0	2	41. Shorting by tools or metal objects
2	2	1	1	0	0	0	0	9	0	3	0	0	2	42. Shorting by birds, snakes, rodents, etc.
0	0	1	0	0	3	0	0	0	0	0	0	0	0	51. Loss of control power
2	1	11	64	5	0	0	0	0	0	0	0	0	0	52. Malfunction of protective relay control device, or auxiliary device.
0	0	0	0	0	0	3	0	0	0	0	0	0	0	61. Low voltage
2	0	0	0	0	0	0	0	0	0	0	0	0	0	62. Low frequency
21	25	33	7	5	45	45	35	18	0	11	10	18	4	99. Other

TABLE 40 - FAILURE CONTRIBUTING CAUSE

ELECTRIC UTILITY POWER SUPPLIES	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS – INSULATED	SWITCHGEAR BUS – BARE	BUS DUCT	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS	Table, Title, Category
														TABLE 40 - FAILURE CONTRIBUTING CAUSE (Col. 44)
2	13	4	0	5	10	8	0	0	6	0	2	0	0	1. Persistent overloading
4	0	1	0	1	6	3	5	0	0	0	0	2	0	2. Above-normal temperatures
0	0	0	0	0	0	1	0	0	0	0	0	0	0	3. Below-normal temperature
0	0	2	0	7	0	0	0	10	0	28	14	13	10	4. Exposure to aggressive chemicals or solvents
2	6	3	0	10	6	4	15	20	17	1	8	22	12	5. Exposure to abnormal moisture or water
0	0	0	0	0	3	0	0	5	0	3	2	0	0	6. Exposure to non-electrical fire or burning
0	0	0	0	2	0	0	0	0	0	0	1	0	0	8. Obstruction of ventilation by foreign objects or material
4	24	17	40	34	32	5	20	10	50	3	30	29	24	9. Normal deterioration from age
38	6	1	0	2	3	0	20	5	11	30	15	2	16	10. Severe wind, rain, snow, sleet, or other weather conditions
2	0	2	0	0	6	0	0	0	0	1	0	0	0	11. Protective relay improperly set
0	0	1	2	15	0	0	0	0	0	0	0	0	0	12. Loss or deficiency of lubricant
0	0	0	0	1	0	0	0	0	0	0	0	0	0	13. Loss or deficiency of oil or cooling medium
0	3	10	3	0	0	0	0	15	6	2	3	0	8	14. Misoperation or testing error
4	3	3	1	5	0	26	40	20	0	2	1	0	0	15. Exposure to dust or other contaminants
45	44	55	53	18	32	53	0	15	11	31	24	31	29	99. Other

TABLE 41 - FAILURE CHARACTERISTIC

ELECTRIC UTILITY POWER SUPPLIES	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS - INSULATED	SWITCHGEAR BUS - BARE	BUS DUCT	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS	Table, Title, Category
%	%	%	%	%	%	%	%	%	%	%	%	%	%	TABLE 41 - FAILURE CHARACTERISTIC (Col. 46)
														Utility Power Supplies (Select code)
10	1	0	0	0	0	0	30	8	10	0	17	0	12	1. Failure of single circuit (no redundant supply)
71	0	1	0	0	0	0	5	0	0	0	7	0	2	2. Failure of one circuit of a double-circuit redundant supply
15	0	0	0	0	0	0	0	0	0	0	0	0	0	3. Failure of both circuits of a double-circuit redundant supply
2	0	1	0	0	0	0	0	8	0	0	0	0	0	4. Failure of all circuits of a three or more circuit redundant supply
0	0	0	0	0	3	0	0	0	0	0	0	0	0	5. Partial failure of a three or more circuit redundant supply
														Transformers (Select Code)
0	90	0	0	0	0	4	0	0	0	0	4	0	2	6. AUtomatic removal by protective equipment
0	1	0	0	0	0	0	0	0	0	0	0	0	0	7. Partial failure reducing capacity
0	7	0	0	0	0	0	0	0	0	0	0	0	0	8. Manual removal

TABLE 41 - FAILURE CHARACTERISTIC

ELECTRIC UTILITY POWER SUPPLIES	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS - INSULATED	SWITCHGEAR BUS - BARE	BUS DUCT	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS	Table, Title, Category
														Circuit Breakers (Select Code)
0	0	5	1	0	0	0	0	0	0	0	0	0	0	9. Failed to close when it should
1	0	9	1	0	0	0	0	0	15	0	0	0	0	10. Failed while opening
0	0	42	1	0	6	0	0	0	0	0	0	0	0	11. Opened when it shouldn't
0	0	7	0	0	0	0	0	0	0	0	0	0	0	12. Damaged while successfully opening
0	0	2	0	0	0	0	0	0	0	0	0	0	0	13. Damaged while closing
0	0	32	0	0	0	0	0	0	0	0	0	0	0	14. Failed while operating (not while opening or closing)
														General (Select Code for any other class)
0	1	0	34	68	65	68	65	71	65	69	65	96	65	15. Failed (this applies to all classes
0	0	1	5	1	0	3	0	13	5	2	2	4	2	16. Failed during testing or maintenance
0	0	1	36	30	0	18	0	0	0	1	2	0	12	17. Damage discovered during testing or maintenance
0	0	0	20	0	16	6	0	0	5	6	3	0	6	20. Partial failure
0	0	0	1	0	10	1	0	0	0	23	1	0	0	99. Other

An interesting point is that in over two thirds of the failures there had been no preventive maintenance, yet inadequate maintenance was only listed in 10 percent of the cases as being responsible for the failure. 16 percent placed the responsibility with the manufacturer, 14 percent with inadequate installation and testing prior to start-up, with 38 percent of the cases reporting reasons for the failure in classes other than those listed in the survey.

The initiating causes varied from transient overvoltage disturbances to insulation breakdown, to mechanical failures, with 30 percent reporting normal deterioration from age as a contributing cause.

Cable Joints

Of the failures reported, 87 percent were repaired in place, with just over half being repaired on a round-the-clock basis. Almost all of the failures resulted in damaged insulation, primarily from flashovers to ground, which were initiated by insulation breakdowns, transient overvoltages, or mechanical failure.

29 percent of the respondents felt that normal deterioration from old age contributed to the failure, while 35 percent blamed abnormal moisture or exposure to aggressive chemicals. Inadequate installation and testing were considered responsible for 50 percent of the failures. 60 percent of the respondents reported that no preventive maintenance had been performed, but only 18 percent blamed the failure on inadequate maintenance.

Cable Terminations

Of the reported cable termination failures, 60 percent were repaired in place with just over half of the repairs being made on a round-the-clock basis. The primary damage was insulation involving either a flashover to ground or other electrical defect. About half of the respondents felt that the failure was initiated by an insulation breakdown, with normal deterioration due to age, severe weather, and exposure to abnormal moisture or aggressive chemicals contributing significantly to the problem. 39 percent felt that inadequate installation and testing prior to start-up was primarily responsible, while 22 percent felt that inadequate maintenance should be blamed. This also seems to correspond to the reporting that in 40 percent of the cases no preventive maintenance had been performed in over two years.

General Conclusions

Electrical Equipment

The general picture from Tables 38 and 35 spotlights inadequate maintenance as a significant factor in the suspected responsibility for failures. Yet the owner appears willing to work round the clock to fix failures after they have occurred. Lack of cleaning and lubrication is apparent on disconnect switches, buses, open wire, cable, cable joints, cable terminations, and motors.

Electric Utility Power Supplies

Many of the results shown in Tables 33–38 are not really applicable for electric utility power supplies because the questions asked are not well suited. The importance of the utility supply was indicated by 91 percent of respondents making repairs on a round-the-clock basis. The failures were predominantly flashovers involving ground, caused by lightning during severe weather or by dig-ins or vehicular accident. Outside agencies, probably the local utility, were predominantly responsible for the failure with preventive maintenance having no apparent effect on the cases reported.

The data reported under "failure characteristic" in Table 41 are of special significance in the case of double- or triple-circuit electric utility power supplies. In particular, the failure rate can

TABLE 42 - SIMULTANEOUS FAILURE OF ALL CIRCUITS IN ELECTRIC UTILITY POWER SUPPLIES

% of 145 Failures from Table 41	Number of Failures	Utility Power Supplies - Failure Characteristic from Table 41
15%	22	3. Failure of both circuits of a double-circuit redundant supply
2%	3	4. Failure of all circuits of a three or more circuit redundant supply
17%	25	Total number of simultaneous failures of all circuits in a double or more circuit redundant supply

be calculated for the simultaneous failure of all circuits in a double- or triple-circuit electric utility power supply.

From Table 3 of Part 1 [1] the sample size is 210.7 unit-years for a double- or triple-circuit electric utility power supply. A double- or triple-circuit supply operating for one year is counted as one unit-year. It is possible to calculate a failure rate from these data as follows:

$$\frac{25}{210.7} = 0.119$$ failures per year for simultaneous failure of all circuits in a double- or triple-circuit electric utility power supply.

Some discrepancies were found in the data on the number of installed units for double- and triple-circuit electric utility power supplies. See the discussion in Part 1 [1] on this point.

Discrepancies

A survey such as this one often obtains some data that appear to contain errors. Sometimes the results look ridiculous. However, some of the ridiculous looking results may actually be correct. Some of the errors are believed due to a misinterpretation of the question by the respondent.

The data in Tables 31–41 have been published without attempting to correct discrepancies or errors. A brief list of some possible discrepancies is given.

Table 36: The damaged part of one percent of failed circuit breakers is a tap changer. The damaged part of three percent of failed cables is a bearing. Winding insulation is shown as the damaged part in failures of cables, bus ducts, and motor starters.

Table 39: Three percent of the failures in disconnect switches were initiated by low voltage.

References

[1] IEEE Committee Report, "Report on reliability survey of industrial plants, Part I: Reliability of electrical equipment," this issue, pp. 213-235.

Discussion

J. Krasnodebski, N. M. Thompson, D. H. Cooke, A. W. W. Cameron, S. Basu, and T. J. Ravishanker (Ontario Hydro, Toronto, Ont., Canada):

1) *Quality of Input Data:* The confidence level of data in a survey of this kind cannot be assessed by mathematics only. One key problem is the adequacy of records and completeness of data. Some of the apparent discrepancies noted in the paper seem to indicate quite substantial omissions in records. Unless the industries involved keep much better failure records than we have done to date, this is not surprising. The first requirement of a useful reliability program is an adequately complete and accurate system for recording failures and consequences (in outage terms).

TABLE A
GENERATORS

Forced Outages

EEI Report

Sample Size (unit-years)	Number of Occurrences per Unit-Year	Outage Hours per Occurrence
204	0.142	91.8
404	0.839	126.5
705	0.521	54.4
483	0.393	125.6

	IEEE Reliability Survey		
Type of Drive	Sample Size (unit-years)	Number of Occurrences per Unit-Year	Outage Hours per Occurrence
Steam turbines*	761.8	0.032	165.0
Jet engines			
Gas turbines	89.4	0.638	23.1
Diesel engines	59.4	0.067	127.0

*EEI results are for generators 60–89 MW.

The requirements for better records, along with the detail involved in the report forms, indicate that acquiring useful data of this kind is time consuming.

It is suggested that, if a choice is necessary, it might be preferable to have a limited (but statistically adequate) number of plants establish a reliably complete recording and reporting system rather than increase the size of the sample under current record systems.

2) *Survey Results on Equipment Failures:* The failure rate is given in failures per unit-year. Is year in this context a calendar year or 8760 hours of plant or equipment operating time? If the failure rate is given per calendar year, were adjustments made for plants operating for 40 hours per week against those operating for up to 168 hours per week?

3) *Discussion of Equipment:*

Motors: It is suspected that the discrepancy in failure rates results from the different application of the two types of motors. Synchronous motors are usually applied only in engineered situations and are carefully designed for the application. Large synchronous motors are usually slow speed. Induction motors are mass produced, purchased off the shelf at the lowest cost, and usually operated to take advantage of any service factor. The survey figures are probably correct but cannot be used for comparison of reliability, leading to a conclusion that synchronous motors are more reliable. It is a comparison of apples and oranges.

Switchgear Bus: The paper states that the reported data are the opposite to what they should be. The reported figures may be correct. Manufacturers regularly reduce the spacing between buses and the spaces between phases and ground when they use insulated bus. As the conductor insulation is usually also reduced by design and occasionally by inferior material standards compared to that on insulated cables. and workmanship is frequently less than perfect, failures on this type of gear are probably at least as common as those on air-insulated equipment.

Circuit Breakers: The failure rate for circuit breakers appears much too low. It must of course be a function of the frequency of operation as well as lapsed time. We did not find a definition of circuit breaker failure, which we believe should differ from cable, transformer, or other static device failures. Circuit breaker failures should be based on failure to operate satisfactorily either to remain closed or to open or to close when called upon. It should be clear whether these figures include failures caused by auxiliaries such as instrument transformers, relays, and control switches. Since any calculation of the reliability of a power system would be made unreasonably complex by attempts to treat all these devices individually, a figure for circuit breaker failures which includes them is usually required by the designer.

Generators: For the generators in the electrical power industry a good source of data exists in the EEI "Report on Equipment Availability for Twelve-Year Period 1960–1971." The comparison between the failure rates and average repair time contained in that report and the survey discussed are shown in Table 43. EEI data quoted for steam turbine driven generators are for the size class 60–89 MW, which is probably larger than the average size of a corresponding generator included in the industrial survey.

It can be seen that the EEI failure rate for steam turbine driven generators based on forced outages is higher by a factor of 5 than in the industrial survey. For gas turbines, failure rates contained in both reports are of the same order, while the outage duration quoted in the EEI report is higher. 54 failures in 5.5 unit years in the petroleum industry can probably be explained by the start-up troubles.

In summary, experience in the utility industry seems to explain results obtained in the industrial survey to a large degree.

4) *Causes of Failure:*

a) How important is the age of equipment? It is mentioned only as a "contributing cause," second in frequency only to "other." Are there economic replacement times, or does obsolescence usually come first?

b) Should the inference be drawn that reliability of industrial equipment, which is reasonably well suited to its job, depends mainly on 1) stringent acceptance testing, especially overvoltage testing, 2) adequate cleaning, and 3) proper lubrication of bearings?

5) *Additional Suggestions for Analysis:* Consideration should be given to add the manufacturer of the main class of equipment to provide information on reliability of different manufacturers.

Carl Becker (Cleveland Electric Illuminating Company, Cleveland, Ohio 44101): The Reliability Subcommittee did an outstanding job in assembling and correlating the mountainous volume of data in a simple, easy to understand tabulation. I would like to add some discussion that I feel would help the value of these tables and add to the accuracy of future studies. My two main points are 1) the downtime per failure on a single-circuit utility supply is extremely high (possibly by a factor of five), and 2) the equation for the dollars lost per interruption may be improved by using other than the kilowatt demand and kilowatthour usage as bases.

My company gathers, codes, and analyzes by computer all interruptions to our three quarter million customers. The average downtime per customer on our distribution system (which is a single-circuit radial supply) has been between 51 and 61 min for five of the past six years. Our service area experienced a catastrophic storm during 1969 which caused the average downtime per customer to jump to 124 min. In addition, my company is of the opinion that no plant should be down for more than 4 h (barring major catastrophies). A report is therefore written for each interruption exceeding 4 h in duration, and these reports are extremely few in number. Furthermore, 13 utilities have polled their reliability statistics for customers fed from the distribution system and found the average downtime per interruption for 1971 to be approximately 1½ h long. The average downtimes ranged from 0.75 to 3.2 h.

This information shows that the downtime per failure for industrial plants is probably outside the predicted tolerance on the IEEE data. This variance may be due to either a major long disturbance affecting a majority of those industrial plants participating or to misinterpretation of the information required.

For over five years I have worked with our customers in regard to reliability problems. My experience has shown that the plant investment, labor cost, and value of product is a better gauge of the cost per minute down than would be either maximum kilowatthour demand or usage. For example, I worked with a manufacturer of magnesium parts for military aircraft (I will call this plant A) and another manufacturer of parts for conveyor systems (plant B). The dollar loss for A per minute down was 100 times greater than that for B. However, plant B's demand is 2500 kW and A's demand is 500 kW, which is an indication that the kilowatthour consumptions in these particular cases are not related at all to the economical loss due to a power interruption. In general I find that the cost of downtime is tied heavily to one of the following: 1) the number of employees, 2) the cost of the product in production (piecework), or 3) the dollar output per hour (high production). A combination of these three items would indicate that loss is tied to the dollars out of the plant per unit of time. Therefore I feel that future studies should relate downtime to dollars per minute of plant production, gross plant, etc.

J. W. Beard (Union Carbide Corporation, South Charleston, W. Va. 25303): The report format and the manner in which the information is presented is generally quite adequate. Appendix A (Part I) is somewhat difficult to read because of the reduced print, but I am not suggesting it be upgraded for this report. Because of the many and various pieces of data used for the report, it is understandable that the reader must spend a great deal of time in studying and analyzing the information in order to properly apply it. The "readily" understandable factor should perhaps be given more consideration in defining the criteria for future surveys.

It is my opinion that the most useful types of information presented are:

1) failure rate and failure rate confidence limits;
2) failure, damaged part;
3) failure type;
4) failure initiating cause;
5) failure contributing cause;
6) failure characteristics.

I believe it is a good assumption that the raw data submitted for many of the other types of information represented were of much lesser accuracy than for these. For example, most plants reporting data for information types such as plant outage cost, critical service loss duration, and loads lost versus time of power outage probably had to draw on someone's memory of each failure and then apply the "best estimate" principle. This factor alone raises the question as to whether these types of information can ever be constructed to have useful

meaning. Except for near catastrophic failures, which result in heavy financial losses, it is doubtful that most plants will spend the money to document this type of data. Furthermore, in a practical sense, when configuring systems and applying electrical equipment, the reliability requirement must be carefully considered for each producing unit served inasmuch as there are many variables that enter into the calculation of downtime losses.

The following suggestions are offered for consideration in any future surveys.

1) Basically concentrate on failure rates and failure causes.

2) Simplify and reduce scope of the survey questionnaire forms (present forms tend to scare users from contributing).

3) Omit asking for types of information such as cost of outage, repair time, plant start-up time, etc.

4) Instruct users *not to* report failures of equipment where reasonable preventative maintenance is not performed.

5) Instruct users *not to* report failures of misapplied equipment.

6) Instruct users *not to* include equipment installed prior to January 1, 1968.

7) Instruct users to give "in-service" date (energized) of all equipment units, not just on the reported failures.

8) Define "failure" as "damage to equipment sufficiently severe to force an outage by either manual or automatic removal of voltage." (Keep in mind that failures caused by the conditions in 4) and 5) are not to be reported.)

Part I: There seemed to be a great deal of confusion by the respondents on the information desired for electric power supplies. Thus the published failure rates may be questionable. It is my opinion that the questionnaire form for this was too nondescript. Perhaps one way to clearly describe the power supplies on which information is desired would be to include on the form simple single-line diagrams of the more common types of utility services.

It is my opinion that the lack of response by many companies was due primarily to poor and/or nonexistent records. A major contributing cause may have been the massive amount of information asked for.

The Reliability Subcommittee's judgement that a minimum of 8 to 10 observed failures was required for "good" accuracy when estimating equipment failure rates seems reasonable.

The value chosen for the confidence interval (0.90) was a good choice. The inclusion of confidence limits curves (Fig. 1) adds measurably to the report.

I generally concur with the Subcommittee's discussion comments. Their discussion of some of the results presented in the tables reinforces my feeling that the survey was too broad in scope, and the information submitted by the plants too ambiguous for meaningful interpretation.

While the sample sizes would be made smaller, as a general rule I feel that equipment should be grouped by voltage class. For example, in Table 2 one grouping of cable terminations is for 601-15 000 V. In this instance it would be especially helpful to know the failure rate on 15-kV cable terminations alone.

Part II: As stated in my general comments, I feel that it is not practical to generate reasonably accurate information of these types.

The bases for the units used in cost calculations, dollars per kilowatt plus dollars per killowatthour, are somewhat confusing. Clarification of this would be helpful.

In the Subcommittee's discussion of the cost of power outages, item 2), I must disagree with their thought that electrochemical or heating processes tend to have low outage costs because heat not supplied now can be supplied later.

In the discussion of loads lost versus time of power outage the "time" factor is questionable. Most plants are not equipped to measure short-duration power outages (cycles or even seconds).

Part III: Many of the information types in this part are very important. Some, I feel, are not. I suggest that the questions on failure repair method; failure repair urgency; failure, months since maintenance; and suspected failure responsibility be omitted from future surveys. The remaining types of information may be refined using knowledge gained from this survey.

In the Subcommittee's Summary of Conclusions they report that transient overvoltages were a major cause of failure in equipment such as, for example, transformers and circuit breakers; but I got the impression that much of this was speculation on the part of those responding. The possibility of transient overvoltage should be considered in the investigation of most equipment failures, and IEEE could perform an important service to industry by developing a socalled "evaluation of possibility of transient overvoltage contribution to equipment failures" guide.

Stanley Wells (Union Carbide Corporation, Port Lavaca, Tex. 77979): The Reliability Subcommittee should be congratulated for performing such a comprehensive reliability survey of industrial plants and for providing a very thorough report.

I would like to limit my discussion to Part 3 and, in particular, the preventive maintenance effect on the failure rate. A preventive maintenance program can very definitely have a direct effect on the failure rate of electrical equipment. In the modern automated plant of today, production demands and losses associated with downtime influence maintenance schedules. Equipment is often allowed to remain in operation for periods that exceed desired preventive maintenance time schedules. It is interesting to note that the survey indicates that preventive maintenance can be performed, yet equipment failures occur within a time period which is less than 12 months since preventive maintenance was performed. Our first attempt at a preventive maintenance program met with the same results. The program was reviewed in depth and it was found that it was inadequate and that the preventive maintenance procedures and time schedules should be reviewed and correlated with our failure experience. As experience was gained, the equipment preventive maintenance program developed into a very useful tool to practically eliminate electrical equipment failure. We soon recognized that where preventive maintenance periods were over 24 months or where no preventive maintenance at all was performed, chances of failure were extremely high. This fact is born out in the results of this survey. Table 35, "Failure-Months Since Maintained," has been rearranged to show that a large reduction in failures may be possible if preventive maintenance periods are on a 12- to 18-month basis (Table B).

Let's define preventive maintenance. Preventive maintenance is a system of routine inspections designed to minimize or forestall future equipment operating problems or failures, and which may, depending upon equipment type, require equipment exercising or proof testing. From this definition, the four following items listed under Table 38, "Suspected Failure Responsibility," can be considered a definite part of a maintenance program:

1) manufacture, defective components (locate by inspection or test);
2) application engineering, improper application;
3) inadequate installation and testing prior to start-up (proof test);
4) inadequate maintenance.

It is interesting to note that the survey indicates that these four items are responsible for a very large percentage of failures. The total for each category is listed below.

	Percent
Transformers	55
Circuit breakers	53
Motor starters	77
Motors	42
Generators	41
Disconnect switches	52
Switchgear bus insulated	95
Switchgear bus uninsulated	52
Bus duct	63
Open wire	41
Cable	48
Cable joints	68
Cable terminations	79

To increase the electrical system reliability, each failure should be very carefully analyzed to determine the failure cause, and corrective action to prevent additional failures should be applied to all applicable equipment.

TABLE B
FAILURES

	Less than 12 Months Ago Preventive Maintenance	12 Months or More or No Preventive Maintenance
Transformers	34	65
Circuit breakers	18	81
Motor starters	67	33
Motors	22	78
Generators	58	42
Disconnect switch	8	92
Switchgear bus insulated	10	90
Switchgear bus uninsulated	35	65
Bus duct	25	75
Open wire	1	98
Cable	11	89
Cable joint	18	82
Cable terminations	12	88

R. E. Kuehn (IEEE Reliability Group): The reliability, maintainability, and downtime logistics in the power area is very important and should lend itself to cost analysis, which is the ultimate judge of the value of reliability and maintainability programs. A great deal of data have been analyzed with all the obvious advantages and disadvantages that are entailed in such a data base. Parts 1 and 2 present me with a severe problem as a reliability professional and manager. In both papers a large effort was spent indicating that the survey results do not agree with what the engineering judgment says the results should be; for example, the discussion of Part 1 on motors, generators, cable, and switchgear bus. My quandary is that if I accept your judgment in all logic, I must question the validity of all the data collected, not just for motors, generators, cable, and switchgear bus. A possible procedure would have been to test the hypothesis that a part of the data was significantly different enough from the total grouped data to justify its rejection as part of the group data.

I would like to recommend analysis of variance or multiple regression in analyzing the data. It would appear that a number of possible variables exist and their effects are suitable for quantization. These procedures are covered in [1]-[4].

REFERENCES

[1] R. G. Stokes and F. N. Sehle, "Some life-cycle cost estimates for electronic equipments," in *Proc. 1968 Annu. Symp. on Reliability*, pp. 169-183.
[2] B. L. Retterer, "State of art assessment of reliability and maintainability as applied to ship systems," in *Proc. 1969 Annu. Symp. on Reliability*, pp. 133-145.
[3] H. Dagen, "Multiple regression," in *Proc. 1972 Annu. Symp. on Reliability*," pp. 51-58.
[4] "Cost effectiveness evaluation procedures for shipboard electronic equipment," ARINC Research Publ. 509-01-2-564 and 541-01-1-766.

Tai C. Wong (American Electric Power Service Corporation, New York, N.Y. 10004): The members of the Reliability Subcommittee are to be commended for conducting and analyzing the results of a survey that covers so many elements in industrial power systems.

Perhaps the authors want to clarify why the chi-squared distribution was used in fitting the data and what kind of statistical testing technique was employed to ensure the adequacy of the distribution chosen. The authors did compare the results of the recent survey against those obtained in 1962. The readers should be warned that this is only an observation based on empirical data and that any inference of a trend in the equipment reliability may not be valid. The paper indicates that many of the reported data cover more than one year of operating experience. Because the first survey was conducted twelve years ago, it is felt that the number of years that the different equipments were in service should be published (or the data collected during the next survey if they are not yet available) so that the reader can have a better understanding of the data background when he has to draw further conclusions, beyond the tables presented.

The authors indicated that the purpose of this survey is to make possible the quantitative reliability comparisons between alternative designs of new systems and then use this information in cost-reliability tradeoff studies to determine which type of power distribution system to use. It appears that the authors focus on making the economic tradeoff comparisons based on the available system components at a given time. However, the authors pointed out that the product of failure rate times the average downtime per failure is almost the same in 1973 as in 1962. Perhaps the equipment manufacturers and the industries can establish more dialogues, leading to an answer to the following two questions.

1) Should the equipments have a lower failure rate, but when failing, take longer to repair? or

2) Should the equipments have a higher failure rate, but when failing, need shorter repair time?

In a few instances during the survey, the respondents misinterpreted either the question(s) and/or the definition of the terms, thus leading to unreliable or biased results. This is especially true in the area of preventive maintenance. I might suggest that during the next survey 1) the definition of all terms that are likely to cause confusion in the questionnaire be included, 2) a pilot survey be instituted and any necessary modifications be made to the questionnaire before a full-scale survey is launched, or 3) the survey form be sent out without requesting data, but instead requesting the respondent's interpretations of the questions and the terms used. Then the survey form may be redesigned and data requested.

L. O. Sunderman (Lincoln Electric System, Lincoln, Nebr.): The authors have presented an interesting cross section of costs involved with industrial electric equipment downtime as accumulated by the computer. The data are to be utilized by interested parties in the choice of a reliability design for industrial power distribution systems. The wide range of costs as split into the two parts over 1000 kW and under 1000 kW suggests consideration of other kW brackets at 500, 2500, 5000, 7500, 10 000 kW, etc. The sufficiency of data will dictate breaking points, as the author already questions the cost data below 1000 kW.

In Part 3 the authors have reviewed and presented in excellent tables the results of electric equipment outage reports and repair. It must have been disturbing to note the numerous "other than categories classified." Perhaps further reporting on the "other" category comments, if available, would bring additional results to light.

IEEE Reliability Subcommittee: The authors wish to thank those who presented discussions on these three papers. Some of the suggestions given can be considered for incorporation into future surveys and they can also be used in the analysis of the results.

Several discussers have raised the question about the effect of "in service date" or age on the reliability of electrical equipment. Population data were collected on the average age of equipment in service; these will be published in Part 4. However, the Reliability Subcommittee did not request these data in the survey questionnaire on equipment failures. This subject was considered by the Subcommittee when making up the questionnaire; it was not included because this would have added additional complications to a questionnaire that was already considered too long. This meant that the assumption was made that the failure rate was constant with age. Thus a chi-squared distribution is appropriate for use in calculating the confidence limits of the failure rate. The assumption of a constant failure rate with age can be justified for most electrical equipment based upon reliability surveys made by others.

Mr. Becker and Mr. Beard have raised questions about the accuracy of the cost of power outage data and the attempt to relate it to kilowatts and kilowatthours. Information was collected but not published on the estimated plant outage costs 1) per failure and 2) per hour of downtime. The authors consider that the cost of power outages is an important factor that should be considered in the design of power distribution systems for industrial plants. Since power distribution systems are designed on the basis of kilowatt capacity and kilowatthour of delivered energy, it was felt that it is necessary to attempt to relate the cost of power outages to these two parameters. The approach used by the Reliability Subcommittee is the same as that which has been used by electric power companies in several European countries. The survey result of the median cost of 83¢ per kilowatthour of undelivered energy is in the same range as values obtained from surveys that have been made in Sweden, Norway, France, Italy, and West Germany. The authors agree that the published data of the cost of power outages are more meaningful if related to specific types of plants.

The authors acknowledge Mr. Beard's suggestion that a one-line diagram should be used in the survey of the electric utility supply. A new survey of the electric utility supply is being started, and Mr. Beard's suggestion will be included. This new survey should clear up the problem of the questionable accuracy mentioned by Mr. Beard. The authors acknowledge Mr. Beard's comment questioning the accuracy of the "time" factor in loads lost versus time of power outage in Table 30.

In answer to several questions raised by Mr. Krasnodebski, the authors make the following comments.

1) The failure rates are based upon a calendar year of 8760 h, not upon an operating time, which could be less and would thus result in a higher failure rate than reported in the survey.

2) The failures of circuit breakers are meant to include the auxiliaries.

3) The failure modes of circuit breakers are included in Table 41; this includes "fail to close," "fail to open," etc. However, data were not collected on the number of circuit breaker operations.

4) The Reliability Subcommittee does not consider that it would be appropriate for a technical society such as IEEE to collect and publish reliability data by name of manufacturer.

5) The authors agree that better record keeping of failures would improve survey results. It is expected that future surveys will cover only a few categories of electrical equipment that are considered trouble areas.

6) The authors acknowledge the logic in the very interesting comments made on synchronous motors and switchgear bus and generators.

7) The steam turbine generators in industrial plants probably have constant operation and thus could be expected to have a much lower failure rate than 60–89 MW units in utility applications where the operation was cyclical.

The authors wish to thank Mr. Kuehn for his suggestions in analyzing the data. These suggestions included 1) test hypothesis that part of data can be rejected, and 2) analysis of variance or multiple regression. Mr. Becker has raised a point where this approach for analyzing the data could possibly be tried. Mr. Becker feels that the survey results are too high on the downtime per failure of a single-circuit electric utility supply. This may be true for his system, but perhaps other utilities are not as good as his company's system.

Mr. Wong has raised a warning about drawing the conclusion that equipment reliability has improved since the previous survey conducted 11 to 12 years earlier. A separate paper has been prepared on this subject and will be published in the near future. This paper contains the conclusion that the failure rate of electrical equipment has shown a definite trend of improvement during the 12-year interval.

The authors wish to thank Mr. Wells for his discussion on preventive maintenance. A lot more data on preventive maintenance are being processed and will be included in Part 4. Mr. Wells' Table B shows more failures in the "12 months or more" category than for the "less than 12 months ago" category. The authors would like to point out that the electrical equipment has more unit-years of exposure in the "12 months or more" category and thus could be expected to have more failures. Thus it is not possible to conclude that more frequent preventive maintenance will reduce the failure rate. The Reliability Subcommittee is investigating this subject in further detail and will publish the results in Part 4.

Report on Reliability Survey of Industrial Plants

Part IV
Additional Detailed Tabulation of Some Data Previously Reported in the First Three Parts

Part V
Plant Climate, Atmosphere, and Operating Schedule, the Average Age of Electrical Equipment, Percent Production Lost, and the Method of Restoring Electrical Service after a Failure

Part VI
Maintenance Quality of Electrical Equipment

By
Reliability Subcommittee
Industrial and Commercial Power Systems Committee
IEEE Industry Applications Society

A. D. Patton, *Chair*

C. E. Becker
W. H. Dickinson
P. E. Gannon
C. R. Heising
D. W. McWilliams
R. W. Parisian
S. J. Wells

Industrial and Commercial Power Systems Technical Conference
Institute of Electrical and Electronics Engineers, Inc.
Denver, Colorado
June 3–6, 1974

Also published
IEEE Transactions on Industry Applications
July/August and September/October 1974
Part IV, pp. 456–462
Part V, pp. 463–466
Part VI, pp. 467–468, 681, 469–476

Reprinted from pp. 113–136
in 74CH0855-71A, 1974 I&CPS Technical Conference

Report on Reliability Survey of Industrial Plants, Part IV: Additional Detailed Tabulation of Some Data Previously Reported in the First Three Parts

IEEE COMMITTEE REPORT

Abstract—**An IEEE sponsored reliability survey of industrial plants was completed during 1972. This survey included 30 companies covering a total of 68 industrial plants in the United States and Canada. Additional detailed results are reported on some data that were previously reported in the first three parts. This includes failure modes of circuit breakers, cost of power outages, critical service loss duration time, loss of motor load versus time of power outage, and the effect of failure repair method and repair urgency on the average downtime per failure of electrical equipment. This information is useful in the design of industrial power distribution systems.**

INTRODUCTION AND RESULTS

DURING 1972 the Reliability Subcommittee of the Industrial and Commercial Power Systems Committee completed a reliability survey of industrial plants. This paper presents Part IV of the results from the survey. The first three parts [1]–[3] were published previously. Some of the data in the first three parts caused questions to be raised about the possibility of obtaining additional details. These additional details are being reported in this paper and include the following results.

Table 43 gives failure modes of circuit breakers, including

1) metalclad drawout
   a) 0–600 V
   b) 601–15 000 V
   c) all voltages
2) fixed type (includes molded case)
   a) 0–600 V
   b) all voltages.

Tables 44, 45 give cost of power outages, adding 25 and 75 percentile data to what was previously published.

Table 46 gives critical service loss duration time (maximum length of power failure that will not stop plant production), adding 10, 25, 75, and 90 percentile data to what was previously published.

Paper TOD-74-33, approved by the Industrial and Commercial Power Systems Committee of the IEEE Industry Applications Society for presentation at the 1974 Industrial and Commercial Power Systems Technical Conference, Denver, Colo., June 2–6. Manuscript released for publication April 15, 1974.

Members of the Reliability Subcommittee of the IEEE Industrial and Commercial Power Systems Committee are A. D. Patton, *Chairman*, C. E. Becker, W. H. Dickinson, P. E. Gannon, C. R. Heising, D. W. McWilliams, R. W. Parisian, and S. Wells.

Table 47 lists loss of motor load versus time of power outage, adding the following length of power outage categories:

1) 10 to 15 cycles
2) 15+ to 30 cycles
3) 0.5+ to 2.0 s
4) 2+ to 4.0 s
5) >4.0 s.

Tables 48 through 56 report the effect of failure repair method and failure repair urgency on the average downtime per failure for the following equipment categories:

1) transformers—liquid filled
   a) 601–15 000 V
   b) above 15 000 V
2) circuit breakers—metalclad drawout
   a) 0–600 V
   b) above 600 V
3) motors
   a) induction, 0–600 V
   b) induction, 601–15 000 V
   c) synchronous, 601–15 000 V
4) cable
   a) above ground and aerial, 601–15 000 V
   b) below ground and direct burial, 601–15 000 V

In each of the Tables 43 through 56 reference is made to the tables in Parts I, II, and III where previous results had been reported.

DISCUSSION—FAILURE MODES OF CIRCUIT BREAKERS

The data on failure modes of circuit breakers given in Table 43 show some very interesting results.

Circuit Breakers, 0–600 V

71 percent of the failures of metalclad drawout circuit breakers were "opened when it shouldn't" versus 5 percent of the failures for fixed-type circuit breakers (includes molded case). 77 percent of the failures of fixed-type circuit breakers (includes molded case) were "failed while operating (not while opening or closing)," and only 10 percent of the metalclad drawout failures included this failure mode.

None of the failures reported for either type of circuit breaker were "failed while opening." Only 9 percent and

TABLE 43 - FAILURE MODES OF CIRCUIT BREAKERS - Percent of Total Failures in Each Failure Mode
(Data Previously Reported in Tables 5 and 41)

All Circuit Breakers	Metalclad Drawout- All	Metalclad Drawout- 601-15,000 Volts	Metalclad Drawout- 0-600 Volts All Sizes	*Fixed Type 0-600 Volts All Sizes	*Fixed Type- All	Card-Type 3, Col. 46
%	%	%	%	%	%	FAILURE CHARACTERISTIC
5	5	2	7	8	6	Failed to close when it should
9	12	21	0	0	2	Failed while opening
42	58	49	71	5	4	Opened when it shouldn't
7	6	4	9	5	4	Damaged while successfully opening
2	1	0	0	0	4	Damaged while closing
32	16	24	10	77	73	Failed while operating (not while opening or closing)
1	0	0	0	0	2	Failed during testing or maintenance
1	2	0	3	0	0	Damage discovered during testing or maintenance
1	0	0	0	5	5	Other
100%	100%	100%	100%	100%	100%	Total Percent
-	117	53	59	39	48	Number of Failures in Total Percent
-	7	0	7	1	1	Number Not Reported in Col. 46, Card-Type 3
-	124	-	66	40	49	Total Failures in Table 5

*Includes molded case

5 percent, respectively, of the failures were "damaged while successfully opening." Only 7 to 8 percent of the failures were "failed to close when it should."

It appears that the dominate failure mode for metalclad drawout circuit breakers, 0–600 V, is "opened when it shouldn't." It is possible that some of these failures were external to the breaker and of unknown cause and were blamed on the breaker. Some of these may have been due to improper-setting of the trip current.

The dominate failure mode for fixed-type circuit breakers (includes molded case), 0–600 V, is "failed while operating (not while opening or closing)."

Metalclad Drawout Circuit Breakers, 601–15 000 V

Metal drawout circuit breakers, 601–15 000 V, had 21 percent of the failures classified as "failed while opening" and 4 percent classified as "damaged while successfully opening." Another 24 percent of the failures were classified as "failed while operating (not while opening or closing)." 49 percent of the failures were classified as "opened when it shouldn't;" it is suspected that some of these may have been due to improper setting of the trip current.

It appears that metalclad drawout circuit breakers, 601–15 000 V, have about half of their failures as "opened when it shouldn't" and the other half as "failed while operating or while opening."

DISCUSSION—LOSS OF MOTOR LOAD VERSUS TIME OF POWER OUTAGE

The data on loss of motor load shown in Table 47 indicate that for power outages greater than 10 cycles duration most of the plants lose the motor load. However, for power outages between 1 to 10 cycles duration, only about half as many lose the motor load. Thus, power outages of less than 10 cycles duration may often not result in losing the motor load.

There were many power outages of more than 4.0 s duration, and 35 percent did not lose motor load. It is suspected that many of these did not have a motor load. Some may have had a duplicate feed and thus did not lose the motor load.

DISCUSSION—EFFECT OF FAILURE REPAIR METHOD AND FAILURE REPAIR URGENCY ON AVERAGE HOURS DOWNTIME PER FAILURE

Data were given in Part I on the average hours downtime per failure for 74 categories of electrical equipment. It is known that the downtime after a failure can be affected to a large extent by the failure repair method and the failure repair urgency. The failure repair method includes either repair of the failed component or else replacement with a spare. Some data were given in Tables 33 and 34 of Part III on the failure repair method and the failure repair urgency for whole classes of electrical equipment.

A more detailed study is reported in Tables 48–56 of this paper on the effect of the failure repair method and the failure repair urgency on the average hours downtime per failure. This is only reported for 9 electrical equipment categories, rather than the 74 categories given in Part I. These 9 electrical equipment categories were selected because an adequate sample size existed of the number of failures and because the average downtime per failure was effected significantly by the failure repair method and/or the failure repair urgency.

TABLE 44 - PLANT OUTAGE COST PER FAILURE PER kW OF MAXIMUM DEMAND ($ per kW)
All Industry - USA & Canada
(Data Previously Reported in Tables 22, 24 and 26)

Plant Size	Number of Plants Reporting	Minimum	25% Percentile	Median	75% Percentile	Maximum	Average
All Plants	42	.002	.17	.69	2.55	10.00	1.89
Plants > 1000 kW Max. Demand	32	.002	.09	.32	1.31	7.50	1.05
Plants < 1000 kW Max. Demand	10	.50	1.71	3.68	8.27	10.00	4.59

TABLE 45 - PLANT OUTAGE COST PER HR. DOWNTIME PER kW OF MAXIMUM DEMAND ($ per kWh)
All Industry - USA & Canada
(Data Previously Reported in Tables 23, 25 and 27)

Plant Size	Number of Plants Reporting	Minimum	25% Percentile	Median	75% Percentile	Maximum	Average
All Plants	41	.0009	.18	.83	2.71	27.00	2.68
Plants > 1000 kW Max. Demand	31	.0009	.12	.36	1.20	5.77	.94
Plants < 1000 kW Max. Demand	10	.86	1.83	4.42	12.50	27.00	8.11

TABLE 46 - CRITICAL SERVICE LOSS DURATION (Maximum Length of Power Failure that Will Not Stop Plant Production)
(Data Previously Reported in Table 29)

Industry	Number of Plants Reporting	Average	10% Percentile	25% Percentile	Median	75% Percentile	90% Percentile
All Industry - USA & Canada	55	12.6 min.	5.0 cycles	10.0 cycles	10.0 sec.	15.0 min.	60.0 min.
Chemical	20	4.56 min.	3.2 cycles	8.5 cycles	1.25 sec.	5.0 min.	28.5 min.

TABLE 47 - LOSS OF MOTOR LOAD VERSUS TIME OF POWER OUTAGE
Tabulation of the Percentage of Equipment Failures for Which the Motor Load was Lost
(Data Previously Reported in Table 30)

Length of Equipment Failure	Number of Failures Reported	TYPE OF LOAD LOST Motor		
		Yes	No	Not Known
1 cycle or less	0	0%	0%	0%
1+ to 10- cycles	-	33%	67%	0%
10 to 15 cycles	7	86%	14%	0%
15+ to 30 cycles	28	96%	4%	0%
0.5+ to 2.0 sec.	30	77%	13%	10%
2.0+ to 4.0 sec.	10	100%	0%	0%
>4.0 second	998	64%	35%	0%

TABLE 48 TRANSFORMERS-LIQUID FILLED, 601-15,000 VOLTS
EFFECT OF FAILURE REPAIR METHOD AND FAILURE REPAIR URGENCY
ON THE AVERAGE HOURS DOWNTIME PER FAILURE
(Previous Data Given in Tables 4, 33 and 34)

FAILURE REPAIR METHOD			FAILURE REPAIR METHOD		
Repair	Replace with Spare	Total	Repair	Replace with Spare	
Number of Failures			Average Hours Downtime per Failure		FAILURE REPAIR URGENCY
4	22	26	*	130	1. Requiring round-the-clock all out efforts
10	3	13	342	*	2. Requiring repair work only during regular workday, perhaps with some overtime
0	0	0	-	-	3. Requiring repair work on a non-priority basis
14	25	39	Average 174. Hours		Total

*Small Sample Size

TABLE 49 - TRANSFORMERS-LIQUID FILLED, ABOVE 15,000 VOLTS
EFFECT OF FAILURE REPAIR METHOD AND FAILURE REPAIR URGENCY
ON THE AVERAGE HOURS DOWNTIME PER FAILURE
(Previous Data Given in Tables 4, 33 and 34)

FAILURE REPAIR METHOD			FAILURE REPAIR METHOD		
Repair	Replace with Spare	Total	Repair	Replace with Spare	
Number of Failures			Average Hours Downtime per Failure		FAILURE REPAIR URGENCY
2	5	7	*	*	1. Requiring round-the-clock all out efforts
12	4	16	1842	*	2. Requiring repair work only during regular workday, perhaps with some overtime
0	1	1	-	*	3. Requiring repair work on a non-priority basis
14	10	24	Average 1076. Hours		Total

*Small Sample Size

TABLE 50 - CIRCUIT BREAKERS - METALCLAD DRAWOUT, 0-600 VOLTS
EFFECT OF FAILURE REPAIR METHOD AND FAILURE REPAIR URGENCY
ON THE AVERAGE HOURS DOWNTIME PER FAILURE
(Previous Data Given in Tables 5, 33 and 34)

FAILURE REPAIR METHOD			FAILURE REPAIR METHOD		
Repair	Replace with Spare	Total	Repair	Replace with Spare	
Number of Failures			Average Hours Downtime per Failure		FAILURE REPAIR URGENCY
31	19	50	3.3	3.8	1. Requiring round-the-clock all out efforts
6	1	7	*	*	2. Requiring repair work only during regular workday, perhaps with some overtime
8	1	9	*	*	3. Requiring repair work on a non-priority basis
45	21	66	Average 147. Hours		Total

*Small Sample Size

TABLE 51 - CIRCUIT BREAKERS - METALCLAD DRAWOUT, ABOVE 600 VOLTS
EFFECT OF FAILURE REPAIR METHOD AND FAILURE REPAIR URGENCY
ON THE AVERAGE HOURS DOWNTIME PER FAILURE
(Previous Data Given in Tables 5, 33 and 34)

FAILURE REPAIR METHOD			FAILURE REPAIR METHOD		
Repair	Replace with Spare	Total	Repair	Replace with Spare	
Number of Failures			Average Hours Downtime per Failure		FAILURE REPAIR URGENCY
34	12	46	83.1	2.1	1. Requiring round-the-clock all out efforts
3	9	12	*	*	2. Requiring repair work only during regular workday, perhaps with some overtime
0	0	0	-	-	3. Requiring repair work on a non-priority basis
37	21	58	Average 109. Hours		Total

*Small Sample Size

TABLE 52 - MOTORS - INDUCTION, 0-600 VOLTS
EFFECT OF FAILURE REPAIR METHOD AND FAILURE REPAIR URGENCY
ON THE AVERAGE HOURS DOWNTIME PER FAILURE
(Previous Data Given in Tables 7, 33 and 34)

FAILURE REPAIR METHOD			FAILURE REPAIR METHOD		
Repair	Replace with Spare	Total	Repair	Replace with Spare	
Number of Failures			Average Hours Downtime per Failure		FAILURE REPAIR URGENCY
12	19	31	44.7	6.6	1. Requiring round-the-clock all out efforts
175	2	177	123	*	2. Requiring repair work only during regular workday, perhaps with some overtime
0	5	5	-	*	3. Requiring repair work on a non-priority basis
187	26	213	Average 114. Hours		Total

*Small Sample Size

TABLE 53 - MOTORS - INDUCTION, 601-15,000 VOLTS
EFFECT OF FAILURE REPAIR METHOD AND FAILURE REPAIR URGENCY
ON THE AVERAGE HOURS DOWNTIME PER FAILURE
(Previous Data Given in Tables 7, 33 and 34)

FAILURE REPAIR METHOD			FAILURE REPAIR METHOD		
Repair	Replace with Spare	Total	Repair	Replace with Spare	
Number of Failures			Average Hours Downtime per Failure		FAILURE REPAIR URGENCY
14	10	24	88.1	*	1. Requiring round-the-clock all out efforts
93	48	141	83.6	34.7	2. Requiring repair work only during regular workday, perhaps with some overtime
6	0	6	*	-	3. Requiring repair work on a non-priority basis
113	58	171	Average 76. Hours		Total

*Small Sample Size

TABLE 54 - MOTORS - SYNCHRONOUS, 601 - 15,000 VOLTS
EFFECT OF FAILURE REPAIR METHOD AND FAILURE REPAIR URGENCY
ON THE AVERAGE HOURS DOWNTIME PER FAILURE
(Previous Data Given in Tables 7, 33 and 34)

FAILURE REPAIR METHOD			FAILURE REPAIR METHOD		
Repair	Replace with Spare	Total	Repair	Replace with Spare	
Number of Failures			Average Hours Downtime per Failure		FAILURE REPAIR URGENCY
28	2	30	198	*	1. Requiring round-the-clock all out efforts
55	8	63	201	*	2. Requiring repair work only during regular workday, perhaps with some overtime
1	0	1	*	-	3. Requiring repair work on a non-priority basis
84	10	94	Average 175.Hours		Total

*Small Sample Size

TABLE 55 - CABLE - ABOVE GROUND & AERIAL, 601-15,000 VOLTS
EFFECT OF FAILURE REPAIR METHOD AND FAILURE REPAIR URGENCY
ON THE AVERAGE HOURS DOWNTIME PER FAILURE
(Previous Data Given in Tables 13, 33 and 34)

FAILURE REPAIR METHOD			FAILURE REPAIR METHOD		
Repair	Replace with Spare	Total	Repair	Replace with Spare	
Number of Failures			Average Hours Downtime per Failure		FAILURE REPAIR URGENCY
46	4	50	9.0	*	1. Requiring round-the-clock all out efforts
11	8	19	*	*	2. Requiring repair work only during regular workday, perhaps with some overtime
2	2	4	*	*	3. Requiring repair work on a non-priority basis
59	14	73	Average 40.4 Hours		Total

*Small Sample Size

TABLE 56 - CABLE - BELOW GROUND & DIRECT BURIAL, 601-15,000 VOLTS
EFFECT OF FAILURE REPAIR METHOD AND FAILURE REPAIR URGENCY
ON THE AVERAGE HOURS DOWNTIME PER FAILURE
(Previous Data Given in Tables 13, 33 and 34)

FAILURE REPAIR METHOD			FAILURE REPAIR METHOD		FAILURE REPAIR URGENCY
Repair	Replace with Spare	Total	Repair	Replace with Spare	
Number of Failures			Average Hours Downtime per Failure		
17	57	74	26.5	19.0	1. Requiring round-the-clock all out efforts
2	33	35	*	77.8	2. Requiring repair work only during regular workday, perhaps with some overtime
3	3	6	*	*	3. Requiring repair work on a non-priority basis
22	93	115	Average 95.5 Hours		Total

*Small Sample Size

In several cases there is a disparity in the downtime between the "average" and the cases where work is done "round the clock." When making availability calculations, this should be considered when deciding what value to use for the downtime after a failure.

Transformers, Liquid Filled

Transformers, above 15 000 V, had an average downtime per failure of 1842 h when sent out for repair without round-the-clock urgency. This compares with an overall average of 1076 h for all outage times, which included several cases of replacement with a spare. Thus it can be concluded that repair gives a much longer outage time than replacement with a spare for transformers, above 15 000 V.

Transformers, 601-15 000 V, had an average downtime per failure of 342 h when sent out for repair without round-the-clock urgency. This compares with 130 h for replacement with a spare while working round the clock. Thus it can be concluded that repair gives a much longer outage time for transformers, 601-15 000 V, than replacement with a spare while working round the clock.

Circuit Breakers, Metalclad Drawout

Metalclad drawout circuit breakers, 0-600 V, had an average downtime per failure of 3.3 h to 3.8 h when fixing the failure with round-the-clock efforts. This compares with an overall average of 147 h for all outage times. Thus it can be concluded that 24 percent of the outages of metalclad drawout circuit breakers, 0-600 V, had low urgency for fixing the failure, and that these 24 percent of the failures resulted in increasing the average downtime per failure from 3.8 h to 147 h.

Metalclad drawout circuit breakers above 600 V, had an average downtime per failure of 109 h for all outages. However, when round-the-clock effort was applied it only took 83 h for repair and only took 2.1 h for replacement with a spare. This shows that it is possible to reduce the downtime by having a spare and working round the clock when fixing metalclad drawout circuit breakers, above 600 V.

Motors

Most users of synchronous motors, 601-15 000 V, did not have a spare. Thus the average downtime per failure was 175 h for all failures.

Induction motors, 601-15 000 V, had an average downtime per failure of 35 h for replacement with a spare, compared to 84 to 88 h for repair. Induction motors, 0-600 V, had an average downtime per failure of 6.6 h for replacement with a spare while working round the clock. This compares with 123 h for repair and not working round the clock.

Cables

Cables, above ground and aerial, 601-15 000 V, had an average downtime per failure of 9 h for repair when working round the clock. This compares with 40 h for all failures. This shows that it is possible to reduce the downtime by working round the clock when fixing cables, above ground and aerial, 601-15 000 V.

Cables, below ground and direct burial, 601-15 000 V, had an average downtime per failure of 96 h for all failures. However, this was only 19 to 27 h when working round the clock. This shows that it is possible to reduce the downtime by working round the clock when fixing cables, below ground and direct burial, 601-15 000 V.

DISCUSSION—COST OF POWER OUTAGES

Data are given in Tables 44 and 45 on the cost of power outages to industrial plants. This has added 25th and 75th percentile data to what had previously been reported in Part II. These were added because of the wide spread in the cost of power outages to industrial plants.

REFERENCES

[1] W. H. Dickinson *et al.*, "Report on reliability survey of industrial plants, part I: Reliability of electrical equipment," *IEEE Trans. Ind. Appl.*, vol. IA-10, pp. 213-235, Mar./Apr. 1974.
[2] W. H. Dickinson *et al.*, "Report on reliability survey of industrial plants, part II: Cost of power outages, plant restart time, critical service loss duration time, and type of loads lost versus time of power outages," *IEEE Trans. Ind. Appl.*, vol. IA-10, pp. 236-241, Mar./Apr. 1974.
[3] W. H. Dickinson *et al.*, "Report on reliability survey of industrial plants, part III: Causes and types of failures of electrical equipment, the methods of repair, and the urgency of repair," *IEEE Trans. Ind. Appl.*, vol. 14-10, pp. 242-252, Mar./Apr. 1974.

Report on Reliability Survey of Industrial Plants, Part V: Plant Climate, Atmosphere, and Operating Schedule, the Average Age of Electrical Equipment, Percent Production Lost, and the Method of Restoring Electrical Service after a Failure

IEEE COMMITTEE REPORT

***Abstract*—An IEEE sponsored reliability survey of industrial plants was completed during 1972. This survey included the plant climate, atmosphere, and operating schedule, the average age of electrical equipment, percent production lost, and the method of restoring electrical service after a failure. The results are reported from the survey of 30 companies covering 68 plants in nine industries in the United States and Canada. This information is useful in the design of industrial power distribution systems.**

INTRODUCTION AND RESULTS

DURING 1972 the Reliability Subcommittee of the Industrial and Commercial Power Systems Committee completed a reliability survey of industrial plants. This paper presents Part V of the results from the survey. The first three parts [1]–[3] were published previously; some of the data of lesser importance were not published at that time but are presented in this paper. Included in Part V are

- Table 57—Failure Forewarning for Public Utility Power Interruption Only,
- Table 58—Percent Production Lost,
- Table 59—Method of Service Restoration,
- Table 60—Average Age of Electrical Equipment,
- Table 61—Plant Climate,
- Table 62—Plant Atmosphere,
- Table 63—Plant Operating Schedule.

These data are useful when using the results published in Parts I, II, III, IV [4], and VI [5]. This information is also useful in the design of industrial power distribution systems. The data on average age of electrical equipment and plant operating schedule provide answers to some points raised in the written discussion to Part I.

Paper TOD-74-33, approved by the Industrial and Commercial Power Systems Committee of the IEEE Industry Applications Society for presentation at the 1974 Industrial and Commercial Power Systems Technical Conference, Denver, Colo., June 2-6. Manuscript released for publication April 15, 1974.

Members of the Reliability Subcommittee of the IEEE Industrial and Commercial Power Systems Committee are A. D. Patton, *Chairman*, C. E. Becker, W. H. Dickinson, P. E. Gannon, C. R. Heising, D. W. McWilliams, R. W. Parisian, and S. Wells.

TABLE 57 - FAILURE FOREWARNING for PUBLIC UTILITY POWER INTERRUPTION ONLY

Percent	Col. 25 Card-Type 3
97%	1. If no forewarning was given
3%	2. If forewarning was given
—	For other types of failure, leave blank
100%	Total Percent
172	Total Interruptions Reported

SURVEY FORM

The survey form is shown in Appendix A of Part I [1]. The information reported in this paper came from 1) card type 3, columns 25, 53, and 58; 2) card type 2, column 33; and 3) card type 1, columns 9–11 and 13. The definition of *failure* is given in Part I.

RESPONSE TO SURVEY

A total of 30 companies responded to the survey questionnaire, reporting data covering 68 plants in nine industries in the United States and Canada. For the purpose of reporting results in this paper, Part V, the number of industries were reduced from nine down to five plus an "all other" category. The five industries selected were the ones for which equipment failure rate data were reported in Tables 3 through 19, Part I. All of the remaining industries were combined into an "all other" category in Tables 61–63 on plant climate, plant atmosphere, and plant operating schedule.

DISCUSSION—FOREWARNING FOR PUBLIC UTILITY POWER INTERRUPTION

Only 3 percent of the time was a failure forewarning given for a public utility power interruption to the industrial plant. Data from Table 3, Part I, and Table 57, Part V, indicate that a large percentage of these interruptions were on double- or triple-circuit supplies. Forewarning can be important to plants with a single circuit. It can also be important to plants containing a double circuit with manual switchover.

TABLE 58 - PERCENT PRODUCTION LOST

Col. 53 Card Type 3 — Percent Production Lost	ELECTRIC UTILITY POWER SUPPLIES	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS-INSULATED	SWITCHGEAR BUS-BARE	BUS DUCT	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS
	%	%	%	%	%	%	%	%	%	%	%	%	%	%
0 None	41	22	19	85	24	80	20	20	17	30	62	28	33	47
1 0-30 Percent	32	63	73	13	73	5	75	60	33	55	25	60	58	35
2 Above 30 Percent	27	15	8	2	3	15	5	20	50	15	13	13	9	18
Total Percent	100	100	100	100	100	100	100	100	100	100	100	101	100	100
Total Failures Reported	202	101	177	168	561	85	101	20	24	20	108	223	45	51

TABLE 59 - METHOD OF SERVICE RESTORATION

TOTAL	ELECTRIC UTILITY POWER SUPPLIES	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS - INSULATED	SWITCHGEAR BUS - BARE	BUS DUCT	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS	Col. 58 Card Type 3
%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	Give method of restoring service to plant
7	1	3	6	0	5	20	0	58	25	20	13	14	28	19	1 Primary selection - manual
2	8	0	1	0	0	0	0	0	5	0	4	5	8	0	2 Primary selection - automatic
11	1	25	6	0	14	33	0	17	10	10	2	20	32	23	3 Secondary selection - manual
2	1	3	8	0	0	0	0	0	0	0	1	0	8	4	4 Secondary selection - automatic
0+	0	0	0	0	0	0	0	0	5	0	0	0	0	0	5 Network protector operation - automatic
22	5	25	11	12	30	20	3	17	20	35	31	42	24	27	6 Repair of failed component
22	2	39	38	10	29	14	77	0	10	35	6	2	0	12	7 Replacement of failed component with spare
12	81	0	1	0	0	13	0	0	0	0	1	1	0	0	8 Utility restored service
22	1	5	29	78	22	0	20	8	25	0	42	16	0	15	9 Other - explain in remarks
100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	Total Percent
1204	171	75	160	68	318	15	69	12	20	20	103	122	25	26	TOTAL NUMBER REPORTED

TABLE 60 - AVERAGE AGE OF ELECTRICAL EQUIPMENT

TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS-INSULATED	SWITCHGEAR BUS-BARE	BUS DUCT	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS	
NUMBER OF INSTALLED UNITS													Age
6	989	101	104	0	0	0	0	0	30	15	0	12	1 Less than 1 year old
694	3691	3162	1884	9	909	646	1998	1206	12	1019	1385	3314	2 1-10 years od
835	1944	608	3643	77	552	691	555	13640	472	1831	2338	5712	3 More than 10 years old

TABLE 61 - PLANT CLIMATE (for entire plant site)
TABLE 62 - PLANT ATMOSPHERE (for entire plant site)

ALL INDUSTRY	CHEMICAL	METAL	PETROLEUM	RUBBER AND PLASTICS	TEXTILE	ALL OTHER	Table, Title, Card-Type 1 Column No.
NUMBER OF PLANTS							TABLE 61 - PLANT CLIMATE (Col. 9)
							Average of Daily Maximums for Hottest Month
							Temperature / Relative Humidity (RH) (measured at noon to 2 PM ST)
14	8	1	3	0	1	1	1 Hot (> 90F) High (> 55 RH)
3	3	0	0	0	0	0	2 Hot (> 90F) Moderate (50-55 RH)
12	0	0	0	0	0	12	3 Hot (> 90F) Low (< 50 RH)
14	4	1	2	0	0	7	4 Moderate (80-90F) High (> 55 RH)
16	5	1	0	1	1	8	5 Moderate (80-90F) Moderate (50-55RH)
6	1	0	1	2	1	1	6 Moderate (80-90F) Low (< 50 RH)
1	0	0	0	0	0	1	7 Low (<80F) High (>55 RH)
2	0	0	2	0	0	0	8 Low (< 80F) Moderate (50-55 RH)
0	0	0	0	0	0	0	9 Low (< 80F) Low (< 50 RH)
							TABLE 62 - PLANT ATMOSPHERE (Col. 10)
34	2	1	7	0	2	22	1 Clean to slightly polluted air
5	4	0	1	0	0	0	2 With salt spray and corrosive chemicals
0	0	0	0	0	0	0	3 With salt spray and dust or sand
0	0	0	0	0	0	0	4 With salt spray only
13	8	0	0	1	1	3	5 With corrosive chemicals and dust or sand
4	4	0	0	0	0	0	6 With corrosive chemicals only
2	0	0	0	0	0	2	7 With dust or sand only
5	0	2	0	2	0	1	8 With conductive dust
1	0	0	0	0	0	1	9 Other

TABLE 63 - PLANT OPERATING SCHEDULE

ALL INDUSTRY	CHEMICAL	METAL	PETROLEUM	RUBBER AND PLASTICS	TEXTILE	ALL OTHER	Title, Card-Type 1 Column No.
NUMBER OF PLANTS							HOURS PER DAY (Col. 11)
0	0	0	0	0	0	0	Less than 8
9	2	0	1	0	0	6	8
0	0	0	0	0	0	0	9 to 15
19	0	2	0	0	0	17	16
0	0	0	0	0	0	0	17 to 23
40	19	1	7	3	3	7	24
							DAYS PER WEEK (Col. 13)
0	0	0	0	0	0	0	Less than 5
30	1	2	1	2	0	24	5
3	1	0	0	0	0	2	6
35	19	1	7	1	3	4	7

DISCUSSION—PERCENT PRODUCTION LOST

The most severe category of failure in an industrial plant is where above 30 percent of the production is lost. Data from Table 58 show that the following percent of equipment class failures resulted in losing above 30 percent of the production.

Switchgear bus—bare	50 percent
Electric utility power supplies	27 percent
Switchgear bus—insulated	20 percent
Cable terminations	18 percent
Bus duct	15 percent
Transformers	15 percent
Generators	15 percent
Open wire	13 percent
Cable	13 percent
Cable joints	9 percent
Circuit breakers	8 percent
Motors	3 percent
Motor starters	2 percent

It can be seen that failures of switchgear bus and electric utility power supplies often result in losing above 30 percent of the production.

DISCUSSION—METHOD OF SERVICE RESTORATION

The data on method of electrical service restoration to plant is shown in Table 59. A percentage breakdown of the total shows the following results.

Replacement of failed component with spare	22 percent
Repair of failed components	22 percent
Other	22 percent
Utility service restored	12 percent
Secondary selection—manual	11 percent
Primary selection—manual	7 percent
Primary selection—automatic	2 percent
Secondary selection—automatic	2 percent
Network protector operation—automatic	0+ percent

The most common methods of service restoration are replacement of failed component with a spare or repair of failed component. Only 22 percent of the time is primary selection or secondary selection used; this would indicate that most power distribution systems are radial.

DISCUSSION—AVERAGE AGE OF ELECTRICAL EQUIPMENT

Many respondents to the reliability survey of industrial plants submitted data covering a ten-year period. Thus it is not surprising to see that Table 60 shows a large population that is more than ten years old. The following percent of installed units are classified as more than ten years old.

Bus duct	92 percent
Open wire	92 percent
Generators	90 percent
Motors	65 percent
Cable	64 percent
Cable joints	63 percent
Cable terminations	63 percent
Transformers	54 percent
Switchgear bus—insulated	52 percent

Motor starters, disconnect switches, switchgear bus—bare, and circuit breakers had over 50 percent of the installed units one to ten years old.

15 percent of the circuit breakers were less than one year old. All other equipment classes had less than 6 percent of the installed units less than a year old.

DISCUSSION—PLANT CLIMATE AND ATMOSPHERE

Data on plant climate and plant atmosphere are given in Tables 61 and 62. 43 percent of the plants were in a hot climate, 53 percent in a moderate climate, and only 4 percent in a low climate (cold climate). 43 percent of the plants had high relative humidity, 31 percent had moderate relative humidity, and 26 percent had low relative humidity. 53 percent of the plants had a plant atmosphere classified as "clean to slightly polluted air." The other 47 percent had an atmosphere with some contamination.

DISCUSSION—PLANT OPERATING SCHEDULE

The data on plant operating schedule are given in Table 63. 52 percent of the plants operated 7 days per week, 4 percent for 6 days, and 44 percent for 5 days. 59 percent of the plants operated 24 h per day, 28 percent for 16 h, and 13 percent for 8 h.

REFERENCES

[1] W. H. Dickinson *et al.*, "Report on reliability survey of industrial plants, part I: Reliability of electrical equipment," *IEEE Trans. Ind. Appl.*, vol. IA-10, pp. 213–235, Mar./Apr. 1974.
[2] W. H. Dickinson *et al.*, "Report on reliability survey of industrial plants, part II: Cost of power outages, plant restart time, critical service loss duration time, and type of loads lost versus time of power outages," *IEEE Trans. Ind. Appl.*, vol. IA-10, pp. 236–241, Mar./Apr. 1974.
[3] W. H. Dickinson *et al.*, "Report on reliability survey of industrial plants, part III: Causes and types of failures of electrical equipment, the methods of repair, and the urgency of repair," *IEEE Trans. Ind. Appl.*, vol. IA-10, pp. 242–249, Mar./Apr. 1974.
[4] A. D. Patton *et al.*, "Report on reliability survey of industrial plants, part IV: Additional detailed tabulation of some data previously reported in the first three parts," this issue, pp. 456–462.
[5] A. D. Patton *et al.*, "Report on reliability survey of industrial plants, part VI: Maintenance quality of electrical equipment," this issue, pp. 467–476.

Report on Reliability Survey of Industrial Plants, Part VI: Maintenance Quality of Electrical Equipment

IEEE COMMITTEE REPORT

***Abstract*—An IEEE sponsored reliability survey of industrial plants was completed during 1972. This included maintenance quality, the frequency of schedule maintenance, and the failures caused by inadequate maintenance. The results are reported from the survey of 30 companies covering 68 plants in nine industries in the United States and Canada. This information is useful in the design of industrial power distribution systems.**

INTRODUCTION

A KNOWLEDGE of maintenance quality of electrical equipment in industrial plants is useful information when planning the maintenance program of industrial power distribution systems. In addition it is useful to know how this correlates with the normal maintenance cycle and the failures blamed on inadequate maintenance. During 1972 the Reliability Subcommittee of the Industrial and Commercial Power Systems Committee completed a reliability survey of industrial plants. This paper presents Part VI of the results from the survey. The first three parts [1]–[3] were published previously. Table 38 from Part III reported that inadequate maintenance was blamed for between 8 to 30 percent of the failures of electrical equipment. This information has caused the Reliability Subcommittee to make a further study of the failure data; the results from this study are being reported in this paper. Included in Part VI are the results for 12 main classes of electrical equipment on

1) equipment population versus a) maintenance quality and b) normal maintenance cycle;
2) failures due to all causes versus a) failure, months since maintained, and b) maintenance quality;
3) failures due to inadequate maintenance versus a) failure, months since maintained, and b) maintenance quality.

The "maintenance quality" is an opinion that was reported by each participant in the survey. The four classifications used were "excellent," "fair," "poor," and "none." The "normal maintenance" cycle is the frequency of performing preventive maintenance.

Paper TOD-74-33, approved by the Industrial and Commercial Power Systems Committee of the IEEE Industry Applications Society for presentation at the 1974 Industrial and Commercial Power Systems Technical Conference, Denver, Colo., June 2–6. Manuscript released for publication April 15, 1974.
Members of the Reliability Subcommittee of the IEEE Industrial and Commercial Power Systems Committee are A. D. Patton, *Chairman*, C. E. Becker, W. H. Dickinson, P. E. Gannon, C. R. Heising, D. W. McWilliams, R. W. Parisian, and S. Wells.

SURVEY FORM

The survey form is shown in Appendix A of Part I [1]. The information reported in this paper came from 1) card type 2, col. 34 (maintenance, normal cycle); 2) card type 2, col. 36 (maintenance quality); 3) card type 3, col. 34 (failure, months since maintained); 4) card type 3, col. 40 (suspected failure responsibility). The definition of *failure* is given in Part I.

RESPONSE TO SURVEY

A total of 30 companies responded to the survey questionnaire, reporting data from nine industries in the United States and Canada. Every plant did not report all the information called for in card type 2, columns 34 and 36. Every failure report did not have filled out all of the information called for in card type 3, columns 34 and 40; a total of 1469 failures had this information filled in and are reported here in Part VI, and 240 of these failures were blamed on inadequate maintenance. Differences in the number of failures and unit-years reported here in Part VI and those previously reported in Part I and Part III can be explained from the preceding.

STATISTICAL ANALYSIS

The subject of statistical analysis of equipment failures is discussed in Part I [1]. Confidence limits for the failure rate are shown in Fig. 1 of Part I. The Reliability Subcommittee concluded that eight failures is an adequate sample size for reporting failure rates in the summary in Table 2, Part I. In a few cases, failure rate data were reported in Tables 3 through 19, Part I, where there were less than eight failures.

In this paper several cases are reported in Tables 67 through 78, where the failure rate contains less than eight failures; these cases have been marked "small sample size."

SURVEY RESULTS

Results are tabulated for 12 main equipment classes in Table 64 where the equipment population is given versus 1) maintenance quality and 2) normal maintenance cycle.

Table 65 summarizes the percent of each electrical equipment class population versus the maintenance quality. Table 66 summarizes the percent of each electrical equipment class population versus the normal maintenance cycle.

Results are tabulated for each of the 12 main equipment classes in Tables 67 through 78, where the number of failures is given for 1) failures due to all causes and 2)

Correction to "Report on Reliability Survey of Industrial Plants, Part VI: Maintenance Quality of Electrical Equipment"

IEEE COMMITTEE REPORT

TABLE 64 - POPULATION OF ELECTRICAL EQUIPMENT VERSUS MAINTENANCE QUALITY & NORMAL MAINTENANCE CYCLE

MAINTENANCE QUALITY Card-Type 2 Col. 36	MAINTENANCE, NORMAL CYCLE Card-Type 2 Col. 34				
	Less Than 12 Months	12 - 24 Months	More Than 24 Months	No Preventive Maintenance	Total
	Population: Unit-Years				
TRANSFORMERS					
Excellent	19	8,904	2,314	0	11,237
Fair	292	3,081	5,961	0	9,334
Poor	0	130	210	0	340
None	0	0	0	39	39
Total	311	12,115	8,485	39	20,950
CIRCUIT BREAKERS					
Excellent	297	11,640	5,014	0	16,951
Fair	1	12,620	11,860	0	24,481
Poor	0	0	1,810	0	1,810
None	0	0	0	7,608	7,608
Total	298	24,260	18,684	7,608	50,850
MOTOR STARTERS					
Excellent	126	2,724	0	0	2,850
Fair	68	4,348	3,435	0	7,851
Poor	0	680	427	70	1,177
None	0	0	0	0	0
Total	194	7,752	3,862	70	11,878
MOTORS					
Excellent	14,650	1,372	1,259	17	17,298
Fair	121	21,930	2,958	0	25,009
Poor	0	0	74	70	144
None	0	0	0	13	13
Total	14,771	23,302	4,291	100	42,464
GENERATORS					
Excellent	104.4	380.7	0	0	485.1
Fair	74.4	279.8	0	0	354.2
Poor	0	0	0	0	0
None	0	0	0	0	0
Total	178.8	660.5	0	0	839.3
DISCONNECT SWITCHES					
Excellent	0	6,287	1,435	0	7,722
Fair	58	426	2,642	0	3,126
Poor	0	402	0	0	402
None	0	0	0	7,365	7,365
Total	58	7,115	4,077	7,365	18,615

(see pp. 681 for the second part of Table 64)

TABLE 64 - POPULATION OF ELECTRICAL EQUIPMENT VERSUS MAINTENANCE QUALITY & NORMAL MAINTENANCE CYCLE

MAINTENANCE QUALITY Card-Type 2 Col. 36	MAINTENANCE, NORMAL CYCLE Card-Type 2 Col. 34				
	Less Than 12 Months	12-24 Months	More Than 24 Months	No Preventive Maintenance	Total
	Population: Unit-Years				
SWITCHGEAR BUS - INSULATED**					
Excellent	0	364	12,160	0	12,524
Fair	0	1,706	0	0	1,706
Poor	0	0	0	0	0
None	0	0	0	1,541	1,541
Total	0	2,070	12,160	1,541	15,771
SWITCHGEAR BUS - BARE**					
Excellent	0	1,854	27,580	0	29,434
Fair	0	19,440	2,826	0	22,266
Poor	0	769	0	0	769
None	0	0	0	369	369
Total	0	22,063	30,406	369	52,838
OPEN WIRE (Unit = 1,000 Circuit Feet)					
Excellent	0	2,217	1,014	0	3,231
Fair	0	103	2,630	0	2,733
Poor	0	0	0	0	0
None	0	0	0	680	680
Total	0	2,320	3,644	680	6,644
CABLE (Unit = 1000 Circuit Feet)					
Excellent	600	329	400	0	1,329
Fair	7	7,900	8,519	135	16,561
Poor	0	23	563	35	621
None	0	0	203	9,920	10,123
Total	607	8,252	9,685	10,090	28,634
CABLE JOINTS					
Excellent	0	9,374	311	0	9,685
Fair	12	2,800	23,530	0	26,342
Poor	0	0	1,483	0	1,483
None	0	0	0	12,110	12,110
Total	12	12,174	25,324	12,110	49,620
CABLE TERMINATIONS					
Excellent	2,500	14,290	15,650	0	32,440
Fair	0	1,452	35,200	1,170	37,822
Poor	0	0	845	0	845
None	0	0	0	54,280	54,280
Total	2,500	15,742	51,695	55,450	125,387

**Unit - Number of Connected Circuit Breakers or Instrument Transformer Compartments

failures due to inadequate maintenance, versus 1) failure, months since maintained, and 2) maintenance quality. Failure rate calculations are also given in Tables 67 through 78; these calculations used the population data from Table 64.

Table 79 summarizes the number of failures for all equipment classes combined versus the maintenance quality. Table 80 summarizes the number of failures for all equipment classes combined versus the months since maintained.

GENERAL CONCLUSIONS—MAINTENANCE QUALITY

The maintenance quality is an opinion that was reported by each participant in the survey. The major portion of the electrical equipment population in the survey had a maintenance quality that was classified as excellent or fair. Less than 5 percent of the population in each equipment class (except for motor starters) were classified as poor. Four equipment categories had between 24 percent to 43 percent of the population classified as "none" under maintenance quality; this included cable termination (43 percent), disconnect switches (40 percent), cable (35 percent), and cable joints (24 percent).

Maintenance quality had a significant effect on the percent of all failures that were blamed on inadequate maintenance. In the "poor" category 33 percent of all failures were blamed on inadequate maintenance. This compares with 18 percent for fair maintenance and 12 percent for excellent maintenance. The "none" category for maintenance quality also had 12 percent of all failures blamed on inadequate maintenance; but 82 percent of these failures were for equipment classes that do not require much maintenance (cable, cable terminations, cable joints,

TABLE 65 - PERCENT OF ELECTRICAL EQUIPMENT POPULATION VERSUS MAINTENANCE QUALITY (All Data Taken from Table 64)

MAINTENANCE QUALITY Card-Type 2 Col. 36	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS-INSULATED	SWITCHGEAR BUS-BARE	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS
	%	%	%	%	%	%	%	%	%	%	%	%
Excellent	54	33	24	41	58	41	79	56	49	5	20	26
Fair	44	48	66	59	42	17	11	42	41	58	53	30
Poor	2	4	10	0+	0	2	0	1	0	2	3	1
None	0+	15	0	0+	0	40	10	1	10	35	24	43
Total	100	100	100	100	100	100	100	100	100	100	100	100

TABLE 66 - PERCENT OF ELECTRICAL EQUIPMENT POPULATION VERSUS NORMAL MAINTENANCE CYCLE (All Data Taken from Table 64)

MAINTENANCE, NORMAL CYCLE Card-Type 2 Col. 34	TRANSFORMERS	CIRCUIT BREAKERS	MOTOR STARTERS	MOTORS	GENERATORS	DISCONNECT SWITCHES	SWITCHGEAR BUS-INSULATED	SWITCHGEAR BUS-BARE	OPEN WIRE	CABLE	CABLE JOINTS	CABLE TERMINATIONS
	%	%	%	%	%	%	%	%	%	%	%	%
Less than 12 Months	1	1	2	35	21	0+	0	0	0	2	0+	2
12-24 Months	58	47	65	55	79	38	13	42	35	29	25	13
More than 24 Months	41	37	32	10	0	22	77	57	55	34	51	41
No Preventive Maintenance	0+	15	1	0+	0	40	10	1	10	35	24	44
Total	100	100	100	100	100	100	100	100	100	100	100	100

TABLE 67 - NUMBER OF TRANSFORMER
FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3, Col. 34: Less Than 12 Months Ago	12 - 24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	Failures per Unit-Year
	Number of Failures Due to ALL CAUSES					ALL CAUSES
Excellent	22	11	5	0	38	
Fair	10	26	16	1	53	
Poor	2	1	1	1	5	
None	0	0	0	3	3	
Total	34	38	22	5	99	.00473
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	0	1	2	0	3	.00027*
Fair	1	0	6	0	7	.00075*
Poor	0	0	0	1	1	.00294*
None	0	0	0	0	0	.00000*
Total	1	1	8	1	11	.00053

* Small Sample Size

TABLE 68 - NUMBER OF CIRCUIT BREAKER
FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3, Col. 34: Less Than 12 Months Ago	12 -24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	Failures per Unit-Year
	Number of Failures Due to ALL CAUSES					ALL CAUSES
Excellent	13	60	3	1	77	
Fair	18	42	4	1	65	
Poor	0	2	2	0	4	
None	1	0	0	26	27	
Total	32	104	9	28	173	.00340
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	2	1	3	1	7	.00041*
Fair	2	18	2	0	22	.00090
Poor	0	1	2	0	3	.00166*
None	0	0	0	4	4	.00053*
Total	4	20	7	5	36	.00071

* Small Sample Size

TABLE 69 - NUMBER OF MOTOR STARTER
FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3 Col. 34: Less Than 12 Months Ago	12 - 24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	Failures per Unit-Year
	Number of Failures Due to ALL CAUSES					ALL CAUSES
Excellent	13	1	4	0	18	
Fair	45	13	8	0	66	
Poor	1	1	2	0	4	
None	0	0	0	0	0	
Total	59	15	14	0	88	.00741
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	1	0	0	0	1	.00035*
Fair	0	1	3	0	4	.00051*
Poor	1	0	1	0	2	.00170*
None	0	0	0	0	0	—
Total	2	1	4	0	7	.00059*

* Small Sample Size

TABLE 70 - NUMBER OF MOTOR
FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3 Col. 34					Failures per Unit-Year
	Less Than 12 Months Ago	12 - 24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	ALL CAUSES
	Number of Failures Due to ALL CAUSES					
Excellent	56	14	7	0	77	
Fair	58	280	90	11	439	
Poor	0	0	2	0	2	
None	0	0	0	0	0	
Total	114	294	99	11	518	.01221
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	8	1	1	0	10	.00058
Fair	2	25	41	2	70	.00280
Poor	0	0	2	0	2	.01390*
None	0	0	0	0	0	.00000*
Total	10	26	44	2	82	.00194

* Small Sample Size

TABLE 71 - NUMBER OF GENERATOR
FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3 Col. 34					Failures per Unit-Year
	Less Than 12 Months Ago	12 - 24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	ALL CAUSES
	Number of Failures Due to ALL CAUSES					
Excellent	14	9	0	0	23	
Fair	1	4	0	0	5	
Poor	0	0	0	0	0	
None	0	0	0	0	0	
Total	15	13	0	0	28	.03360
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	3	0	0	0	3	.00618*
Fair	0	2	0	0	2	.00565*
Poor	0	0	0	0	0	
None	0	0	0	0	0	
Total	3	2	0	0	5	.00596*

* Small Sample Size

TABLE 72 - NUMBER OF DISCONNECT SWITCH
FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3 Col. 34					Failures per Unit-Year
	Less Than 12 Months Ago	12 - 24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	ALL CAUSES
	Number of Failures Due to ALL CAUSES					
Excellent	4	0	1	0	5	
Fair	4	5	4	0	13	
Poor	0	0	16	0	16	
None	0	0	0	67	67	
Total	8	5	21	67	101	.00542
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	0	0	1	0	1	.00013*
Fair	0	4	1	0	5	.00160*
Poor	0	0	0	0	0	.00000*
None	0	0	0	7	7	.00095*
Total	0	4	2	7	13	.00070

* Small Sample Size

TABLE 73 - NUMBER OF SWITCHGEAR BUS-INSULATED FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3 Col. 34: Less Than 12 Months Ago	12 - 24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	Failures per **Unit-Year
	Number of Failures Due to ALL CAUSES					ALL CAUSES
Excellent	2	3	10	0	15	
Fair	0	4	1	0	5	
Poor	0	0	0	0	0	
None	0	0	0	0	0	
Total	2	7	11	0	20	.00127
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	0	0	6	0	6	.00048*
Fair	0	0	1	0	1	.00059*
Poor	0	0	0	0	0	
None	0	0	0	0	0	.00000*
Total	0	0	7	0	7	.00044*

* Small Sample Size
**Unit = Number of Connected Circuit Breakers or Instrument Transformer Compartments

TABLE 74 - NUMBER OF SWITCHGEAR BUS-BARE FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3 Col. 34: Less Than 12 Months Ago	12 - 24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	Failures per **Unit-Year
	Number of Failures Due to ALL CAUSES					ALL CAUSES
Excellent	2	1	1	0	4	
Fair	4	6	2	2	14	
Poor	2	0	0	0	2	
None	0	0	0	3	3	
Total	8	7	3	5	23	.00044
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	0	0	0	0	0	.00000*
Fair	1	1	2	0	4	.00018*
Poor	0	0	0	0	0	.00000*
None	0	0	0	1	1	.00271*
Total	1	1	2	1	5	.00009*

* Small Sample Size
**Unit = Number of Connected Circuit Breakers or Instrument Transformer Compartments

TABLE 75 - NUMBER OF OPEN WIRE FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3 Col. 34: Less Than 12 Months Ago	12 - 24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	Failures per **Unit-Year
	Number of Failures Due to ALL CAUSES					ALL CAUSES
Excellent	0	1	3	0	4	
Fair	1	8	85	0	94	
Poor	0	0	0	0	0	
None	0	0	0	10	10	
Total	1	9	88	10	108	.01628
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	0	1	1	0	2	.00062*
Fair	0	1	30	0	31	.01132
Poor	0	0	0	0	0	—— *
None	0	0	0	0	0	.00000*
Total	0	2	31	0	33	.00497

* Small Sample Size
** Unit = 1,000 Circuit Feet

TABLE 76 - NUMBER OF CABLE
FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3 Col. 34: Less Than 12 Months Ago	12 - 24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	Failures per **Unit-Year ALL CAUSES
	Number of Failures Due to ALL CAUSES					
Excellent	5	6	2	21	34	
Fair	18	19	16	6	59	
Poor	0	3	2	21	26	
None	0	0	2	95	97	
Total	23	28	22	143	216	.00755
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	0	0	0	0	0	.00000*
Fair	0	2	0	0	2	.00012*
Poor	0	0	2	6	8	.01290
None	0	0	0	12	12	.00119
Total	0	2	2	18	22	.00077

* Small Sample Size
** Unit = 1,000 Circuit Feet

TABLE 77 - NUMBER OF CABLE JOINT
FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3 Col. 34: Less Than 12 Months Ago	12 - 24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	Failures per Unit-Year ALL CAUSES
	Number of Failures Due to ALL CAUSES					
Excellent	2	4	0	0	6	
Fair	6	5	1	5	17	
Poor	0	0	0	7	7	
None	0	0	0	15	15	
Total	8	9	1	27	45	.00091
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	0	0	0	0	0	.00000*
Fair	1	0	0	0	1	.00004*
Poor	0	0	0	6	6	.00405*
None	0	0	0	1	1	.00008*
Total	1	0	0	7	8	.00016

* Small Sample Size

TABLE 78 - NUMBER OF CABLE TERMINATION
FAILURES VERSUS MONTHS SINCE MAINTAINED AND MAINTENANCE QUALITY

MAINTENANCE QUALITY Card-Type 2 Col. 36	FAILURE, MONTHS SINCE MAINTAINED Card-Type 3 Col. 34: Less Than 12 Months Ago	12 - 24 Months Ago	More Than 24 Months Ago	No Preventive Maintenance	Total	Failures per Unit-Year ALL CAUSES
	Number of Failures Due to ALL CAUSES					
Excellent	3	3	4	0	10	
Fair	3	3	14	3	23	
Poor	0	0	0	1	1	
None	0	0	0	16	16	
Total	6	6	18	20	50	.00040
	Number of Failures Due to INADEQUATE MAINTENANCE (Card-Type 3 Col. 40)					INADEQUATE MAINTENANCE
Excellent	1	1	1	0	3	.00009*
Fair	0	0	5	0	5	.00013*
Poor	0	0	0	0	0	.00000*
None	0	0	0	3	3	.00006*
Total	1	1	6	3	11	.00008

* Small Sample Size

TABLE 79 - NUMBER OF FAILURES VERSUS MAINTENANCE QUALITY FOR ALL EQUIPMENT CLASSES COMBINED

MAINTENANCE QUALITY Card-Type 2 Col. 36	Number of Failures in Tables 67 thru 78 ALL CAUSES	INADEQUATE MAINTENANCE	PERCENT of Failures Due to Inadequate Maintenance
Excellent	311	36	11.6%
Fair	853	154	18.1%
Poor	67	22	32.8%
None	238	28	11.8%
Total	1,469	240	16.4%

TABLE 80 - NUMBER OF FAILURES VERSUS MONTHS SINCE MAINTAINED FOR ALL EQUIPMENT CLASSES COMBINED

FAILURE, MONTHS SINCE MAINTAINED Card-Type 3, Col. 34	Number of Failures in Tables 67 thru 78 ALL CAUSES	INADEQUATE MAINTENANCE	PERCENT of Failures Due to Inadequate Maintenance
Less than 12 Months Ago	310	23	7.4%
12-24 Months Ago	535	60	11.2%
More Than 24 Months Ago	308	113	36.7%
No Preventive Maintenance	316	44	13.9%
Total	1,469	240	16.4%

and disconnect switches). Thus this 12 percent for "none" is explainable and is not inconsistent with what could be expected.

As maintenance quality decreases from "excellent" to "fair" to "poor," the following equipment classes showed an increasing failure rate from failures blamed on inadequate maintenance: transformers, circuit breakers, motor starters, motors, disconnect switches, switchgear bus—bare, open wire, cable, and cable joints. In some of these cases the sample size is smaller than desirable (less than eight failures) in order to conclusively prove this general statement.

OTHER CONCLUSIONS

Circuit Breakers

Approximately 15 percent of the circuit breaker population had a maintenance quality classified as "none." This compares with less than 1 percent of the population for transformers, motors, and generators.

It is of interest to note that data from Table 60, Part V also show that 15 percent of the circuit breaker population was less than one year old; this compares with less than 3 percent of the population for transformers, motors, and generators. This may possibly account for some of the listings of "none" under maintenance quality reported for failures of circuit breakers.

Motors

Motors with a maintenance quality of "fair" had a failure rate due to inadequate maintenance that was five times higher than motors with excellent maintenance quality.

Open Wire

Open wire with a maintenance quality of "fair" had a failure rate due to inadequate maintenance that was more than ten times higher than open wire with excellent maintenance quality.

DISCUSSION—MAINTENANCE QUALITY

From Table 79 it is possible to calculate for all equipment classes combined the ratio of the number of failures from inadequate maintenance to the number of failures from all other causes. This ratio versus maintenance quality is as follows: poor—0.49, fair—0.22, excellent—

0.13. This is a measure of how much improvement can be obtained by upgrading the maintenance quality from poor to fair to excellent. An excellent maintenance program has only 13 percent more failures added by inadequate maintenance, while a poor maintenance program has 49 percent more failures added by inadequate maintenance.

It is apparent from the data that excellent maintenance quality is very important on open wire and on motors.

It would also appear from the data in Table 65 that essentially everyone in the survey did excellent or fair maintenance on transformers, generators, and switchgear bus—bare. However, on circuit breakers 15 percent of the population had "none" and 4 percent had "poor" on maintenance quality. On motor starters 10 percent had "poor" on maintenance quality. Thus, it would appear that everyone did not maintain circuit breakers and motor starters as well as transformers, generators, and switchgear bus—bare.

One of the drawbacks to the results reported under maintenance quality was that there was no objective definition of "excellent," "fair," or "poor." There are no standards for maintenance quality, and thus this data must be considered to be individual judgment. However, data reported under "failure, months since maintained" does not have this same drawback; this data can be considered factual.

DISCUSSION—FAILURE, MONTHS SINCE MAINTAINED

The data in Table 80 show for all equipment classes combined that there is a close correlation between the percent of failures due to inadequate maintenance and the failure, months since maintained.

Failure, Months Since Maintained	Percent of Failures Due to Inadequate Maintenance
Less than 12 months ago	7.4
12–24 months ago	11.2
More than 24 months ago	36.7

Data from Tables 67 through 78 can also be used to calculate similar correlations for several equipment categories; however, in some cases the sample size is smaller than desirable for adequate statistical confidence.

COMMENTS—NORMAL MAINTENANCE CYCLE

A detailed analysis has not been made of the "maintenance, normal cycle" data in Tables 64 and 66. It is possible that some interesting conclusions could also be drawn from an analysis of this data.

REFERENCES

[1] W. H. Dickinson *et al.*, "Report on reliability survey of industrial plants, part I: Reliability of electrical equipment," *IEEE Trans. Ind. Appl.*, vol. 1A-10, pp. 213–235, Mar./Apr. 1974.
[2] W. H. Dickinson *et al.*, "Report on reliability survey of industrial plants, part II: Cost of power outages, plant restart time, critical service loss duration time, and type of loads lost versus time of power outages," *IEEE Trans. Ind. Appl.*, vol. 1A-10, pp. 236–241, Mar./Apr. 1974.
[3] W. H. Dickinson *et al.*, "Report on reliability survey of industrial plants, part III: Causes and types of failures of electrical equipment, the methods of repair, and the urgency of repair," *IEEE Trans. Ind. Appl.*, vol. 1A-10, pp. 242–249, Mar./Apr. 1974.

Cost of Electrical Interruptions in Commercial Buildings

By
Power Systems Reliability Subcommittee Industrial and Commercial Power Systems Committee
IEEE Industry Applications Society

P. E. Gannon*, Coordinating Author*
A. D. Patton, *Chair*

C. E. Becker
M. F. Chamow
W. H. Dickenson
M. D. Harris
C. R. Heising
R. T. Kulvicki
D. W. McWilliams
R. W. Parisian
S. J. Wells

Industrial and Commercial Power Systems Technical Conference
Institute of Electrical and Electronics Engineers, Inc.
Toronto, Canada
May 5–8, 1975

Reprinted from IEEE Conference Record
7SCH0947-1-1A, pp. 123–129

COST OF ELECTRICAL INTERRUPTIONS IN COMMERCIAL BUILDINGS

by

Power Systems Reliability Subcommittee Report
Philip E. Gannon, Coordinating Author1/

Abstract

An IEEE sponsored reliability survey to determine the cost of electrical interruptions in commercial buildings was completed in 1974. The survey form was a simplified version of forms used in 1972 reliability study of industrial plants. The survey included building types and locations, and length and cost of electrical service interruptions. The survey results reflect data from 48 companies covering 55 buildings in the United States. This information is useful in the design of electrical systems for commercial buildings.

Introduction

Knowledge of the cost of power outages, both for normal and critical services, is useful in the design of commercial building power systems, allowing cost-effective judgements to be made with respect to the installation of a second utility company service, an emergency generator, or possibly an uninterruptible power supply.

During 1974, the Reliability Subcommittee of the Industrial and Commercial Power Systems Committee completed a survey of the cost of electrical interruptions in commercial buildings in the United States. Included in this paper are the following results:

1 Cost of power outages to commercial buildings ($ per KWH of undelivered energy).

2 Cost of power outages to commercial buildings ($ per square foot/hr and $ per employee/hr).

3 Critical service loss duration time (length of time before an interruption causes a significant loss).

5 Miscellaneous items relative to provision of auxiliary generators, types of electrical service, and other physical data.

Survey Form

The survey form is shown in Appendix A (two pages). A simple multiple choice or single line fill-in form was utilized in an attempt to reduce the time of the responders, but still provide pertinent data for a meaningful analysis.

Response to Survey

A total of 48 companies reporting on 55 buildings responded to the survey with complete data. Incomplete data, omitting the critical outage cost information was received on 121 additional buildings. Unfortunately, this data was of no value in the present survey. Valid data was submitted almost equally for buildings located in the eastern, central, and western regions of the U.S.A.; with 43 percent of the buildings in downtown areas, 17 percent in urban areas, and 40 percent in suburban areas. Forty-six percent of the buildings were used 5 days per week; 39 percent, 6 days per week; and 15 percent, 7 days per week.

Survey Data Preparation

All of the returned survey forms were reviewed. Useable data was punched onto computer cards for use in data processing.

Survey Results -- Cost of Power Outages

Each respondent was asked to report on the cost of power outages as follows:

1 Dollars per failure -- 15-minute duration, one-hour duration, and greater than one-hour duration; total value of lost operation including wages, damages for delays, loss of computer time, and loss of retail sales minus cost of goods not sold was to be included.

2 Critical service loss duration time -- length of time before an interruption causes a significant loss.

3 Building maximum power demand, and usage, as well as area and number of employees.

The data made it possible to calculate the cost of power outages in terms of dollars per kilowatt-hours of undelivered energy at building peak load.

The average cost of power outages from the survey for the buildings surveyed is given in Table 1.

TABLE 1

AVERAGE COST OF POWER OUTAGES
FOR BUILDINGS IN THE UNITED STATES

All commercial buildings	$7.21/KWH not delivered
Office buildings only	$8.86/KWH not delivered

The average maximum demand was 3,095 KW for all commercial buildings reporting outage costs. The maximum demand for the office buildings was only 3,035 KW.

Additional details of the cost of power outages are given in Tables 2, 3, and 4. The tables present additional data including:

1 Outage costs for "office buildings" as a function of duration of outage for three time periods.

2 Effect of computers on outage costs.

3 Relationship of outage costs to: KWH not delivered, to cost per 1,000 square feet per hour of building affected, and to cost per employee per hour affected.

1/ Other members of Sub-Committee: A.D. Patton Chairman; C.R. Heising, Vice Chairman; C.E. Becker; M.F. Chamow; W.H. Dickinson; M.D. Harris; R.T. Kulvicki; D.W. McWilliams; R.W. Parisian; Stanley Wells

TABLE 2

OUTAGE COSTS FOR "OFFICE BUILDINGS"
AS A FUNCTION OF DURATION
(WITH AND WITHOUT COMPUTERS)

	Sample Size	Maximum	Minimum	Average
<u>15-Minute Duration</u>				
Cost/peak KW hr. not delivered	25	$ 22.22	$ 1.50	$ 7.54
Cost/1,000 sq. ft. of bldg./hr.	26	247.6	10.5	63.8
Cost/employee/hr.	26	52.0	3.0	16.0
<u>1-Hour Duration</u>				
Cost/peak KW hr. not delivered	29	$ 24.93	$ 0.64	$ 6.74
Cost/1,000 sq. ft. of bldg./hr.	32	125.00	5.24	53.12
Cost/employee/hr.	32	34.30	1.25	12.22
<u>Duration 1 Hour</u>				
Cost/peak KW hr. not delivered	13	$100.00	$ 0.16	$ 16.16
Cost/1,000 sq. ft. of bldg./hr.	14	320.00	1.05	68.06
Cost/employee/hr.	14	75.80	0.48	16.41

TABLE 3

OUTAGE COSTS FOR "OFFICE BUILDINGS"
AS A FUNCTION OF DURATION
(WITHOUT COMPUTERS)

	Sample Size	Maximum	Minimum	Average
<u>15-Minute Duration</u>				
Cost/peak KW hr. not delivered	11	$ 10.70	$ 1.50	$ 5.84
Cost/1,000 sq. ft. of bldg./hr.	11	107.4	10.54	49.54
Cost/employee/hr.	11	28.56	3.00	12.56
<u>1-Hour Duration</u>				
Cost/peak KW hr. not delivered	13	$ 13.33	$ 0.91	$ 5.30
Cost/1,000 sq. ft. of bldg./hr.	15	120.0	5.24	49.42
Cost/employee/hr.	15	28.57	1.25	10.64
<u>Duration 1 Hour</u>				
Cost/peak KW hr.	3	$100.00	$ 1.97	$ 36.66
Cost/1,000 sq. ft. of bldg./hr.	3	320.00	48.00	156.00
Cost/employee/hr.	3	50.00	4.00	27.52

TABLE 4

OUTAGE COSTS FOR "OFFICE BUILDINGS"
AS A FUNCTION OF DURATION
(WITH COMPUTERS)

	Sample Size	Maximum	Minimum	Average
<u>15-Minute Duration</u>				
Cost/peak KW hr. not not delivered	14	$ 22.22	$ 1.88	$ 8.89
Cost/1,000 sq. ft. of bldg./hr.	15	250.00	16.57	78.21
Cost/employee/hr.	15	52.00	4.00	18.53
<u>1-Hour Duration</u>				
Cost/peak KW hr. not delivered	16	$ 24.93	$ 1.88	$ 8.30
Cost/1,000 sq. ft. of bldg./hr	17	125.00	15.88	54.52
Cost/employee/hr.	17	34.30	4.00	13.62
<u>Duration 1 Hour</u>				
Cost/peak KW hr. not delivered	10	$ 67.66	$ 0.16	$ 9.81
Cost/1,000 sq. ft. of bldg./hr.	11	226.19	1.05	44.08
Cost/employee/hr.	11	75.82	0.48	12.70

CRITICAL SERVICE LOSS DURATION TIME FOR "ALL BUILDINGS"

	Service Loss Duration Time								
	1 Cycle	2 Cycles	8 Cycles	1 Sec.	3 Sec.	5 Min.	30 Min.	1 Hour	12 Hours
Percent of buildings with critical service loss duration less than or equal to the time indicated.	3%	6%	9%	15%	18%	36%	64%	79%	100%

TABLE 6

CRITICAL SERVICE LOSS DURATION TIME FOR "OFFICE BUILDINGS"

	Service Loss Duration Time								
	1 Cycle	2 Cycles	8 Cycles	1 Sec.	3 Sec.	5 Min.	30 Min.	1 Hour	12 Hours
Percent of buildings with critical service loss duration less than or equal to the time indicated.	5%	10%	15%	25%	30%	30%	70%	75%	100%

TABLE 7

RELATIONSHIP OF AUXILIARY GENERATORS AND SINGLE FEEDER SERVICE TO "ALL BUILDINGS"

	Number of Responses	Buildings with Auxiliary Generation	No Auxiliary Generation and Only Single Feeder
Buildings with computers	23	15	1
Buildings without computers	32	13	7
TOTAL	55	28	8

Survey Results -- Critical Service Loss Duration Time

The amount of time an electrical service can be interrupted before it causes significant losses is a question which our profession has not been able to suitably define. The results of the survey indicate that individual requirements for electrical energy are such that it is probably not possible to establish a general critical service loss duration time. The survey results are shown in Tables 5 and 6.

TABLE 8

TYPE OF ELECTRICAL SERVICE TO "ALL BUILDINGS"

	Number of Responses	Type of Service			
		Single Feeder	Network	Multiple Feeder	Other
Buildings with computers	23	1	8	12	2
Buildings without computers	32	12	10	7	3
TOTAL	55	13	18	19	5

TABLE 9

PHYSICAL DATA -- "ALL BUILDINGS"

Item	Sample Size	Maximum	Minimum	Average
Area, sq. ft. x 10^3	54	2,085	3	400
Number of floors	55	52	1	12
Number of employees	51	7,000	12	1,384
Annual usage - Megawatt hours	52	101,349	210	11,973
Peak Kilowatt demand	52	17,250	95	3,095

TABLE 10

PHYSICAL DATA -- "OFFICE BUILDINGS"

Item	Sample Size	Maximum	Minimum	Average
Area, sq. ft. x 10^3	35	1,600	38	371
Number of floors	35	44	2	13
Number of employees	35	7,000	150	1,651
Annual usage - Megawatt hours	32	51,046	840	9,444
Peak Kilowatt demand	32	17,000	270	3,035

TABLE 11

AVERAGE OF PHYSICAL DATA FOR "ALL BUILDINGS" AND FOR "OFFICE BUILDINGS"

Item	All Buildings	Office Buildings
Megawatt hours/1,000 sq. ft. of buildings area/year	35.5	33.5
Megawatt hours/employee/year	20.2	7.5
Peak Kilowatt demand/1,000 sq. ft. of building area	11.3	11.5
Peak Kilowatt demand/employee	5.0	2.5
Employees/1,000 sq. ft. of building area	3.9	4.7

Thirty-six percent of "all buildings" reporting could be without electrical energy for 5 minutes before the lack of energy was considered to be critical, while 6 percent could be without energy for only 2 cycles and 3 percent for only one cycle before significant losses were incurred.

Fifty percent of the "office buildings" reporting could be without electrical energy for 5 minutes before the lack of energy was considered to be critical, while 10 percent could be without energy for only 2 cycles, and 5 percent for only one cycle before significant losses were incurred.

Precautionary measures taken to minimize critical outages in buildings where computers are installed are indicated in Table 7, where 65 percent (15 of 23) of the buildings reporting have auxiliary generating units. Only 4 percent (1 of 23) of the buildings reporting have no auxiliary generation and are served by a single feeder from the utility company. A like comparison is shown for buildings not having computers; in these instances, 41 percent of the buildings have auxiliary generation and 22 percent are served by single feeders from the utility company.

Table 8 shows the type of electrical service to all buildings reporting. Eighty-seven percent of the buildings with computers have network or multiple feeder service, while 53 percent of the buildings without computers have network or multiple feeder service.

Survey Results -- Demand and Usage Data

Each respondent was asked to report gross floor area, number of floors, number of employees, and electrical energy usage and demand. While not directly related t the subject of this paper, the data is of interest, ar will perhaps allow the reader to make a better judgement of the validity of the data presented previously. The details are given in Tables 9, 10, and 11.

It is believed that the employee data for the "All Buildings" category may not be valid, since it appears that not all employees were reported for some multi-function buildings, the office/retail category in particular.

Conclusions and Discussion of Results

1 Cost of Power Outages (Tables 1, 2, 3, and 4)

a There is a wide spread in the cost of power outages (KWH not delivered) in commercial buildings. Even within like types of buildings, with or without computers, there is a great difference in the costs assigned.

b The cost per KWH not delivered increases greatly when the outage duration time exceeds one hour. An exception to this is buildings with computers.

It is probable that for outages of less than one hour, employees may remain partially productive and the temperature of their environment remains tolerable. For longer outages, employees may have to be furloughed for the remainder of the day.

c The cost of power interruptions for buildings with computers varies from $8.89/KWH average for outages of 15-minutes duration to $9.81/KWH for outages of greater than one hour. It is suspected that the small differential is due to the fact that a short duration as well as a long outage renders the computer inoperable, and the employees are either non-productive during this period or repairing possible damage caused by the outage.

d A comparison of the average costs of outages for commercial buildings with that for industrial plants (Reference 1) is shown in Table 12. The data is interpreted to mean that short-term outages in industrial plants could be more costly than those in commercial buildings, while long-term outages are more costly in commercial buildings.

e Additional information on the cost of power outages in Sweden, Norway, and the United States is contained in Reference 3.

2 Critical Service Loss Duration Time (Tables 5 and 6)

a As would be expected, there is a wide spread in the critical time of a power interruption. This is probably due to the wide variations of type of work being accomplished, the type of equipment involved, and the general work environment. For example, a windowless building in which a sensitive computer operation is performed would be more rapidly affected than a window-wall building performing normal office functions.

b It is suggested that a future survey attempt to define the reasons for the wide variances.

3 Demand and Usage Data (Tables 9, 10, and 11)

a Of the "all building" data reported, the areas averaged 400,000 square feet, 12 floors in height, with an annual usage of almost 12,000 megawatt hours, and a demand of 3,095 KW. Minimum and maximum data were not available.

TABLE 12

COMPARISON OF AVERAGE COSTS OF POWER OUTAGES IN COMMERCIAL BUILDINGS AND INDUSTRIAL PLANTS

Type	Cost
All commercial buildings	$7.21/KWH not delivered
Office buildings	$8.86/KWH not delivered
Industrial plants — all	$1.89/KW interrupted + $2.68/KWH not delivered

The data for "office buildings" indicate average values within 10 percent of that for "all buildings," except for the number of employees, which is 16 percent greater.

b The average electrical usage for all buildings and for office buildings only is nearly equal when placed on a per unit basis (33.5 KWH/Sq. Ft.) as is the peak demand (11.3 Watts/Sq. Ft. to 11.5 Watts/Sq. Ft.). The relationship of usage and demand to employees does not correlate for all buildings and office buildings only. As mentioned heretofore, the validity of employee data with regard to the Office/Retail category of buildings is questionable. On this basis, no attempt to draw conclusions has been made.

References

1 A.D. Patton, et al, "Report of Reliability Survey of Industrial Plants, Part 4 - Additional Detailed Tabulation of Some Data Previously Reported in the First Three Parts," IEEE I & CPS Conference Record, June 2-6, 1974.

2 W.H. Dickinson, et al, "Report of Reliability Survey of Industrial Plants, Part 2 - Cost of Power Outages, Plant Restart Time, Critical Service Loss Duration Time, and Type of Loads Lost vs. Time of Power Outages," IEEE I & CPS Conference Record, May 14-16, 1973.

3 R.B. Shipley, A.D. Patton, J.S. Denison, "Power Reliability Cost vs. Worth," IEEE Transactions on Power Apparatus and Systems, PAS-91, P. 2204-2212, September/October 1972.

SURVEY FORM ON COST OF ELECTRICAL INTERRUPTIONS IN COMMERCIAL BUILDINGS

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

INDUSTRY AND GENERAL APPLICATIONS GROUP

RELIABILITY SUBCOMMITTEE OF THE INDUSTRIAL & COMMERCIAL POWER SYSTEMS COMMITTEE

Electricity is an integral part of our every day life. If it isn't available -- what is its economic effect? Please help us to find out by filling out this form.

Please address reply to:

A. D. Patton
Texas A & M University
Electric Power Institute
College Station, TX 77843

Date ____________

1. COMPANY NAME (Fill in 3-letter abbreviation of name) ____________

2. BUILDING NO. (Fill in sequence number 1, 2, 3, etc. for building(s) reported on) ____________

3. BUILDING TYPE (Check type which best describes your building):

   ☐ Office ☐ Office/Retail Sales ☐ Office/Retail Sales/Apartment

   ☐ Retail Sales ☐ Other (describe) ____________

4. BUILDING LOCATION (Check applicable items):

   ☐ Downtown; ☐ Urban; ☐ Suburban;

   ☐ USA: Eastern; ☐ USA: Central; ☐ USA: Western

5. BUILDING DATA - GENERAL

   Gross Area, square feet ____________

   Number of Floors ____________

   Average Usage of Building: Hours/Day ________ Days/Week ________

   Estimated Number of Office Employees (if any) ____________

   Estimated Annual Retail Sales (if any) ____________

   Is Auxiliary or Emergency Generation Provided: ☐ Yes ☐ No

SURVEY FORM - COMMERCIAL BUILDINGS IN USA **Page 2 of 2**

6. BUILDING ELECTRICAL USAGE DATA

Electrical Energy Usage for 12-month Period ____________ KWH

Electrical Maximum Demand for this Period ____________ KW

Type of Service: ☐ Single Feeder; ☐ Network; ☐ Multiple Feeders With Automatic Transfer

☐ Other (Explain) ______________________________

7. COST OF A TOTAL INTERRUPTION OF ELECTRICAL SERVICE TO YOUR BUILDING DURING PEAK PERIOD: (Best Opinion - If no interruptions have occurred, assume hypothetical instances)

a) 15-Minute Duration $ ____________

b) 1-Hour Duration $ ____________

c) _____ Hours Duration $ ____________

Does a, b, or c include losses from an "on-line" electronic computer? ☐ Yes ☐ No

For "Office Buildings" loss should include wages of all employees affected, plus any other direct costs incurred including delays, and damage to equipment. This would include any losses from an "on-line" electronic computer.

For "Retail Sales" cost should include estimated loss of sales minus cost of goods not sold, plus cost of any damage incurred.

8. LENGTH OF INTERRUPTION OF ELECTRICAL SERVICE

If there a definitive length of time before an interruption causes a significant loss? ☐ Yes ☐ No

If "Yes", what is maximum time before significant losses will be incurred? _______ Hours _______ Minutes

Reliability of Electric Utility Supplies to Industrial Plants

By
Power System Reliability Subcommittee
Industrial and Commercial Power Systems Committee
IEEE Industry Applications Society

A. D. Patton, *Chair*

C. E. Becker
M. F. Chamow
W. H. Dickinson
P. E. Gannon
C. R. Heising
M. D. Harris
R. T Kulvicki
D. W. McWillams
R. W. Parisian
S. J. Wells

Industrial and Commercial Power Systems Technical Conference
Institute of Electrical and Electronics Engineers, Inc.
Toronto, Canada
May 5–8, 1975

Reprinted from IEEE Conference Record
75CH0947-1-1A, pp. 131–133

RELIABILITY OF ELECTRIC UTILITY SUPPLIES TO INDUSTRIAL PLANTS

by
Power Systems Reliability Subcommittee
Industrial and Commercial Power Systems Committee
A. D. Patton, Coordinating Author 1/

ABSTRACT

The paper summarizes the results of a 1974 survey of the reliability of electric utility supplies to industrial plants. Results include the average rates of occurrence and durations of power interruptions as a function of type of electric utility supply. This information should help industrial plant operators choose the types of electric utility supplies best suited to their plants.

INTRODUCTION

The electric utility supply reliability survey reported here is a followup to the 1972 survey of the reliability of electrical equipment in industrial plants.[1,2] The 1972 survey showed that the electric utility supply is the most fallible "component" of an industrial plant system and therefore deserves careful consideration.

Certain of the data in the earlier survey were subject to possible error due to misinterpretation of the survey form. Hence, a prime objective of the present survey was to improve the accuracy of data on electric utility supplies. A second objective was to provide more detailed and definitive data on electric utility supply interruption rates and average durations as a function of the number of supply circuits, the type of switching scheme, and the voltage of the supply circuits. A third objective was to obtain data from a larger number of plants than in the 1972 survey thereby permitting interruption rates and average durations to be determined with greater precision. A total of 87 plants provided usable data, almost triple the number of plants providing data on electric utility supplies in the 1972 survey. Survey response broken down by industry is as follows: cement = 2, chemical = 14, metal = 4, petroleum = 30, pulp and paper = 1, rubber and plastics = 4, and other manufacturing = 32.

It should be emphasized that electric utility supply reliability is a function of a number of factors not directly identified in the data presented here. Included in these reliability-influencing factors are line exposure, weather and other environmental conditions, and utility operating and maintenance practice. Thus, the electric utility supply reliability data given in this paper represents average performance and should not be used in preference to specific data when this is available. Methods are available for computing the reliability performance of an electric utility supply when the reliability performance parameters of utility system components are known.[3]

SURVEY QUESTIONNAIRE

The survey questionnaire requested the following data for each electric utility supply.

1. Type of industry
2. Type of electric utility supply
    a. Number of utility circuits supplying the plant
    b. Mode of operation if more than one supply circuit: all circuit breakers normally closed, manual throw-over scheme, or automatic throw-over scheme
    c. Voltage of utility circuits supplying the plant
    d. Type of supply circuits: overhead or underground
    e. A sketch of the electric utility supply system
3. The period of time covered by the survey report. (Respondents were asked to limit their response to the period January 1, 1968 to the present.)
4. The number of interruptions to the plant due to loss of the electric utility supply during the time period of (3).
5. The duration of each electric utility supply interruption, an indication whether service was restored to the plant by a switching operation or by repair or replacement of failed equipment, and, if known, the equipment which failed causing the interruption.

SURVEY DATA SUMMARY AND DISCUSSION

Some respondents to the survey listed voltage dips which caused disruption of plant production as well as complete interruptions of electric utility service. Other respondents commented on production disruptions due to voltage dips without giving details. However, most respondents reported only on complete interruptions of service and this was the intent of the survey. The Subcommittee feels that the sensitivity to voltage dips is a rather unique characteristic of each plant and process and that average interruption rates including voltage dips would not be very meaningful. Therefore, all voltage dip events were removed from the survey data leaving only those interruptions due to complete loss of electric utility service. Hence, the interruption rates given in the summary tables reflect complete loss of electric utility service only. If a plant is sensitive to voltage dips, the rate of such events must be added to the reported interruption rates to obtain the total rate of production disruption due to utility supply troubles.

Almost all respondents indicated that utility supply circuits are overhead rather than underground. Hence, no effort was made to separate supplies with overhead and underground circuits. The data given in the summary tables essentially reflects overhead supply circuits due to the preponderance of such circuits in the survey response.

Preliminary analyses of utility supply interruption rates by industry category indicated no significant differences between industries. Further, there seems to be no good reason why utility supplies of the same type and voltage should differ between industries. Therefore, the data presented in the summary tables is not broken down by industry.

The survey response broken down by number of utility supply circuits, voltage of utility supply circuits, and mode of operation of multiple supply circuit utility supplies is given in Table I.

1/ Members of the Power Systems Reliability Subcommittee are: A. D. Patton, chairman, C. E. Becker, M. F. Chamow, W. H. Dickinson, P. E. Gannon, M. D. Harris, C. R. Heising, R. T. Kulvicki, D. W. McWilliams, R. W. Parisian, and S. Wells.

Table I
Number of Responding Plants
With Electric Utility Supplies
of Various Types

Number of Supply Circuits	
1 circuit	- 20 plants
2 circuits	- 56 plants
3 or more circuits	- 11 plants
Supply Circuit Voltage	
voltage $\leq$ 15 KV	- 22 plants
15 KV < voltage $\leq$ 35 KV	- 17 plants
voltage >35 KV	- 48 plants
Switching Scheme of Multiple Circuit Supplies	
all breakers closed	- 45 plants
manual throwover	- 9 plants
automatic throwover	- 13 plants

Table I shows that two-circuit supplies are the most common among the responding plants. A much smaller number of plants reported three or more supply circuits. All multiple-circuit supplies are combined in the data tables which follow because such supplies are expected to have similar interruption rates and because of the relatively small sample of supplies with three or more circuits. Responses have been broken into three voltage categories corresponding roughly to distribution voltages, subtransmission voltages, and transmission voltages. This was done because electric utility design and operating practice is rather different at these three function levels. Hence, it can be expected that utility supply reliability will be a function of the system level at which service is provided.

Table I indicates that about two-thirds of the responding plants having multiple circuit utility supplies operate with all circuit breakers closed. That is, service is supplied simultaneously over all supply circuits. Service may also be lost, however, by failures in the plant substation or by a widespread failure in the supplying utility's system. Plants having throwover schemes operate with a single circuit providing normal service. Thus, such plants suffer an interruption any time the normal supply circuit fails. The duration of interruption to such plants is usually limited to the time required to reclose the normal supply circuit or to switch to the alternate supply circuit if the normal circuit is permanently faulted.

Table II summarizes interruption rate and average interruption duration data for single-circuit utility supplies broken down by voltage level. Interruption rates and average durations are given separately for interruptions reported terminated by utility switching operations and by repair or replacement of failed components. Also given are overall interruption rates and average durations.

Tables III and IV show interruption rates and average durations for multiple circuit utility supplies broken down by switching scheme and by voltage level. Table V shows interruption rates and average durations for multiple-circuit utility supplies which operate with all circuit breakers closed broken down by voltage levels. Similar breakdowns by voltage for throwover switching schemes were not possible due to lack of an adequate data base.

Interruption rates and average durations are given in Tables II through V for interruptions where service is restored by: (a) some switching operation or sequence of switching operations in the electric utility system, and (b) repair or replacement of components which failed in the electric utility system. If service can be restored by some automatic or manual switching action in the electric utility system, whether remote or within the utility switchgear at the plant, interruptions are usually much shorter than if repair or replacement of failed components is required to restore service. The reason for providing data on both short-duration switching-terminated interruptions and on long-duration repair-terminated interruptions is because of possible differences in impact on plant operations.

It should be mentioned here that interruption rates and average durations computed from a small number of observed interruptions should be regarded as less accurate than those computed from a larger sample of observations. In particular, Reference [1] shows that interruption rates computed from an observed number of interruptions less than about 8 or 10 may well be in error by plus or minus 50 per cent or more due to random variations alone.

The data of Tables II through V show the expected trends.

(1) Utility supply interruption rates are lowest for multiple circuit supplies which operate with all circuit breakers closed and highest for single-circuit supplies. Tables II and III show that the interruption rate for single-circuit supplies is about six times that of multiple circuit supplies which operate with all circuit breakers closed. Interruption rates for multiple-circuit supplies which operate with a throwover scheme are comparable to those for single-circuit supplies, but throwover schemes have a smaller average interruption duration than single-circuit supplies.

(2) Interruption rates are highest for utility supply circuits operated at distribution voltages and lowest for circuits operated at transmission voltages.

Direct comparisons between interruption rates determined in this survey and in the 1972 survey are not possible in every case, but where possible show somewhat higher values in the present survey. Since the present survey is believed to be more accurate, has a larger data base, and is more up-to-date, the values presented here are to be preferred over those presented in 1972 survey.

REFERENCES

1. Reliability Subcommittee Report, "Report On Reliability Survey of Industrial Plants, Part I: Reliability of Electrical Equipment", IEEE Transactions on Industry Applications, pp. 213-235, March/April 1974.

2. Reliability Subcommittee Report," Report On Reliability Survey of Industrial Plants, Part III: Causes and Types of Failures of Electrical Equipment, the Methods of Repair, and the Urgency of Repair", Ibid., pp. 242-252, March/April 1974.

3. R. Billinton, R. J. Ringlee, and A. J. Wood, Power-System Reliability Calculations, The MIT Press, Cambridge, Mass., 1973.

Table II
Single Circuit Utility Supplies

Voltage Level	Unit-years of History	Number of Interruptions Reported*		Interruptions Per Year**			Average Interruption Duration, Minutes**		
		N_S	N_R	λ_S	λ_R	λ	r_S	r_R	r
v≤15KV	27.62	25	75	.905	2.715	3.621	3.5	165	125
15KV<v≤35KV	12.67	0	21	-	1.657	1.657	-	57	57
v>35KV	71.16	37	60	.527	.843	1.370	1.5	59	37
all	111.45	62	156	.556	1.400	1.956	2.3	110	79

Table III
Multiple Circuit Utility Supplies
All Voltage Levels

Switching Scheme	Unit-Years of History	Number of Interruptions Reported		Interruptions Per Year			Average Interruption Duration, Minutes		
		N_S	N_R	λ_S	λ_R	λ	r_S	r_R	r
all breakers closed	246.17	63	14	.255	.057	.312	8.5	130	31
man. throw-over	42.33	31	5	.732	.118	.850	8.1	84	19
auto. throw-over	64.36	66	11	1.025	.171	1.196	0.6	96	14
all	352.86	160	30	.453	.085	.538	5.2	110	22

Table IV
Multiple Circuit Utility Supplies
All Swiching Schemes

Voltage Level	Unit-Years of History	Number of Interruptions Reported		Interruptions Per Year			Average Interruption Duration, Minutes		
		N_S	N_R	λ_S	λ_R	λ	r_S	r_R	r
v≤15KV	81.31	52	12	.640	.148	.788	4.7	149	32
15KV<v≤35KV	78.00	39	5	.500	.064	.564	4.0	115	17
v>35KV	193.55	69	13	.357	.067	.424	6.1	184	34

Table V
Multiple Circuit Utility Supplies
All Circuit Breakers Closed

Voltage Level	Unit-Years History	Number of Interruptions Reported		Interruptions Per Year			Average Interruption Duration, Minutes		
		N_S	N_R	λ_S	λ_R	λ	r_S	r_R	r
v≤15KV	45.61	8	4	.175	.088	.263	0.7	335	112
15KV<v≤35KV	52.61	18	1	.342	.019	.361	7.0	120	13
v>35KV	147.95	37	9	.250	.061	.311	11.0	203	49

*N_S and N_R are, respectively, the number of service interruptions terminated by switching and by repair or replacement.

**Interruption rates and average durations subscripted S and R are, respectively, rates and durations of interruptions terminated by switching and by repair or replacement. Unsubscripted rates and duration are overall values.

Report of Switchgear Bus Reliability Survey of Industrial Plants and Commercial Buildings

By
Power Systems Reliability Subcommittee
Power Systems Support Committee
Industrial Power Systems Department
IEEE Industry Applications Society

P. O. O'Donnell, ***Coordinating Author***
P. E. Gannon, ***Chair***

J. W. Aquilino
C. E. Becker
W. H. Dickinson
B. Douglas
I. Harley
C. R. Heising
D. Kilpatrick
D. W. McWilliams
R. N. Parisian
A. D. Patton
C. Singh
W. L. Stebbins
H. T Wayne
S. J. Wells

Industrial and Commercial Power Systems Technical Conference
Institute of Electrical and Electronics Engineers, Inc.
Cincinnati, Ohio
June 5–8,1978

Published by
IEEE Transactions on Industry Applications
March/April 1979, pp. 141–147

Report of Switchgear Bus Reliability Survey of Industrial Plants and Commercial Buildings

Power Systems Reliability Subcommittee
Power Systems Support Committee
Industrial Power Systems Department

PAT O'DONNELL, MEMBER, IEEE
COORDINATING AUTHOR[1]

***Abstract*—The Power Systems Reliability Subcommittee of the IEEE Industry Applications Society has been conducting surveys of the reliability of electrical equipment in industrial plants and commercial buildings. Switchgear bus was included in a previous survey published in 1973 and 1974 [1] and generated some controversy concerning bare and insulated bus. For this reason, and also for an ongoing effect to continually update the 1973 and 1974 survey [1], switchgear bus reliability has been investigated in a new survey in 1977, and the results are presented. Reference is made to a paper [2] given at the 1977 Industrial and Commercial Power Systems Technical Conference on reasons for conducting the new survey.**

INTRODUCTION

CURRENT reliability data on failure rate of electrical equipment can provide a valuable tool for the power systems designer or planner. These data can also be a valuable tool for the manufacturer of the equipment concerned.

Many parameters were included in this new survey in an effort to uncover the most influencing factors on the reliability of bare bus and insulated bus and to allow any new obvious and significant applications considerations to be identified. The questionnaire submitted was condensed to a practical and useful form to obtain optimum response in as short of time period as possible.

Results of the survey are presented in tabular form, and discussion is included primarily where adequate response and population data were obtained. Many questions and uncertainties still exist, and the intent of the following presentation is to report the results of the survey with some discussion, but drawing of definite conclusions is left to the reader.

SURVEY FORM

The questionnaire form (Fig. 1) and cover letter used in the survey are included in the Appendix. Total populations data categorize information into major areas of application. An area of primary concern is maintenance because of its obvious relation to failure rate. However, this is the most difficult datum to obtain in complete and uniform format for meaningful results. Responses in this survey did not permit these results to appear, partly due to the respondents' failure to submit information and partly due to the survey format.

Failed unit data were requested in the form shown in the second portion of the questionnaire. The major categories are causes of failure, types of failure, duration of failure, and failed components. This form is less extensive, but more specifically oriented for switchgear bus than in 1973 and 1974 survey [1].

SURVEY RESPONSE

Table I summarizes the survey response including number of buses, companies, and plants. In this survey, bus "unit-year" is defined as the product of the total number of switchgear connected circuit breakers and connected switches reported in a category times the total exposure time. In the previous survey, the unit-year did not include the number of connected switches; that is, only the connected circuit breakers were counted. Table II shows the 1973 and 1974 [1] survey and is included for comparison of responses. The total number of plants in the new survey response is considerably greater than in the 1973 and 1974 survey, but it is interesting to note that unit-year sample size is slightly less. Also some discrepancy appears in the total number of failures reported in Table I and those of some subcategories in tables to follow. This is due to all companies not responding to every category.

SURVEY RESULTS

Insulated and Bare Bus

A major controversy emerged in the results of the 1973 and 1974 survey [1] concerning bare and insulated switchgear bus. Insulated bus, 601-15 000 V, showed a higher failure rate than bare bus, above 600 V, but data were heavily influenced by the chemical industry. The new survey shows the opposite of this, as seen in Table I, with less chemical industry influence. Bare bus, above 600 V, shows a relatively high failure rate, but the sample size is not large, thus making this observation somewhat questionable. With more companies responding in the

Paper ISPD approved by the Power Systems Protection Committee of the IEEE Industry Applications Society for presentation at the 1978 Industrial and Commercial Power Systems Technical Conference, Cincinnati, OH, June 5-9. Manuscript released for publication October 25, 1978.

The author is with El Paso Natural Gas Company, El Paso, TX 79978.

[1] Other members of the subcommittee are Phillip E. Gannon (Chairman), J. W. Aquilino, Carl E. Becker, W. H. Dickinson, Bruce Douglas, Ian Harley, C. R. Heising, Don Kilpatrick, D. W. McWilliams, R. N. Parisian, A. D. Patton, Dr. Chanan Singh, Wayne L. Stebbins, Harold T. Wayne, and Stanley J. Wells.

Company Name and Plant: ______________ ______________________________

Industry Type: ______________________________

Period Reported - From: Month ______________ Year ______________

To: Month ______________ Year ______________

Plant Climate: Temperature __________ Relative Humidity __________

Contamination Level and Type: ______________________________

Total Population:

Bus No.	No. CB's & SW's	Age of Bus (YRS)	Bus Type and Rating: Bare	Insulated	Outdoor	Indoor	Copper	Aluminum	L-L Voltage (KV)	Current (KA)	System Application: L-L Voltage (KV)	Ungrounded	Solid Ground	Imped. Ground	Maintenance Data: Maint Cycle (MO)	Extent of Maintenance
1																
2																
3																
4																
5																
6																

Failed Unit Data:

Bus No.	Failure Primary Cause	Failure Contributing Cause	Type of Failure: Short L-G	Short L-L	Open	Other	Last Maint. (MO)	Restore Data: Round Clock	Normal Hours	Schedule Later	Failure Duration (Hrs.)	Failed Component and Material

Fig. 1. Switchgear bus reliability survey for metalclad and metal enclosed switchgear bus.

new survey but with less overall unit-year sample size, the failure rate for all bus shows to be slightly higher than in the previous survey. But on breaking this down further, bare bus failure rate is higher and insulated bus failure rate is lower in the new survey.

Table I shows the chemical industry data broken out since it is believed to be a major contributor in the controversy of the 1973 and 1974 survey [1]. In the new survey the chemical industry dominated the number of failures in each category, but did not dominate sample sizes. This supports the argument of some that bus utilized in the chemical industry should have a relatively high failure rate, especially in the use of bare bus.

Table I also shows median outage duration time after a failure of each category, in hours per failure. It is important to emphasize that these data are based on many factors, and without sufficient supplement from respondents concerning operating procedures, maintenance type, spare parts inventory, etc., the data relate to a very general or all-inclusive type of information.

Grounding Type

Survey results are shown in Tables III–V. Inadequate response and the general nature of the questionnaire format prohibit sufficient results for this category. It is believed that grounding type related to failures is important data, but data should be specific, for example, in types of failures in ungrounded systems and in impedance value of impedance grounded systems. This category may be pursued in greater detail in the next survey.

TABLE I
SWITCHGEAR BUS: INDOOR AND OUTDOOR

NUMBER OF COMPANIES	NUMBER OF PLANTS IN SAMPLE-SIZE	NUMBER OF BUSES	SAMPLE SIZE UNIT-YR	NUMBER OF FAILURES REPORTED	INDUSTRY	EQUIPMENT SUB-CLASS	FAILURE RATE FAILURE PER UNIT-YEAR	MEDIAN HOURS DOWNTIME PER FAILURE
39	56	444	51391	54	ALL	ALL	.001050	28
28	36	245	24855	28	ALL	INSULATED ABOVE 600V	.001129	28
25	35	199	26592	26	ALL	BARE (ALL VOLTAGES)	.000977	28
17	23	132	22420	18	ALL	BARE 0-600V	.000802	27
14	18	67	4172	8	ALL	BARE ABOVE 600V	.001917	36
14	19	92	7425	15	PETROLEUM CHEMICAL	INSULATED ABOVE 600V	.002020	40
11	13	135	7002	18	PETROLEUM CHEMICAL	BARE (ALL VOLTAGES)	.002570	28
10	11	83	4707	13	PETROLEUM CHEMICAL	BARE 0-600V	.002761	22
7	8	52	2295	5*	PETROLEUM CHEMICAL	BARE ABOVE 600V	*	48

* Small sample-size.

TABLE II
RESULTS OF PREVIOUS SURVEY PUBLISHED IN 1973 AND 1974 [1]
SWITCHGEAR BUS: INDOOR AND OUTDOOR

NUMBER OF PLANTS SAMPLE-SIZE	SAMPLE SIZE (UNIT-YEAR)	NUMBER OF FAILURES REPORTED	INDUSTRY	EQUIPMENT SUB-CLASS	FAILURE RATE FAILURES PER UNIT-YEAR	ACTUAL HOURS DOWNTIME/FAILURE INDUSTRY AVERAGE	MINIMUM PLT. AVG.	MEDIAN PLT. AVG.	MAXIMUM PLT. AVG.
12	11740	20	ALL	INSULATED 601-15000V	0.001700	261	5	26.8	1613
12	32280	11	ALL	BARE 0-600V	0.000340	550	2	24	2520
5	20560	13	ALL	BARE >600V	0.000630	17.3	6.9	13	48
5	4003	15	PETROLEUM CHEMICAL	INSULATED 601-15000V	0.003750	340	18	26.8	1613
3	17270	10	PETROLEUM CHEMICAL	BARE >600V	0.000580	19.3	6.9	42	48

TABLE III
TYPE OF GROUNDING OVERALL, BUS INSULATED AND BUS BARE

	UNGROUNDED	SOLID-GROUND	IMPEDANCE-GROUND	NOT REPORTED	TOTAL
(Unit-Year) Sample-Size	20262	9787	17280	4062	51391
# FAILURE	17	12	23	2*	54
FAILURE RATE	.000839	.001226	.001331	-	.001050

* Small sample size.

TABLE IV
BUS INSULATED

	UNGROUNDED	SOLID-GROUND	IMPEDANCE-GROUND	NOT REPORTED	TOTAL
(Unit-Year) Sample-Size	4626	4274	14270	1685	24855
# FAILURE	7*	4*	16	1*	28
FAILURE RATE			.001121	-	.001126

* Small sample size.

TABLE V
BUS BARE

	UNGROUNDED	SOLID-GROUND	IMPEDANCE-GROUND	NOT REPORTED	TOTAL
(Unit-Year) Sample-Size	15636	5513	3010	2377	26536
# FAILURE	10	8	7*	1*	26
FAILURE RATE	.000640	.001451			.000980

* Small sample size.

TABLE VI
AVERAGE AGE OF SWITCHGEAR BUS

	ALL	INSULATED	BARE
AGE 1-10 yrs.	6526 unit-year	1899 unit-year	4627 unit-year
>10 yrs.	44596 unit-year	22887 unit-year	21709 unit-year

Age of Bus

Tables VI–VIII illustrate how failures of insulated and bare bus relate to age in this survey. An interesting observation here is that newer bus appears to experience a higher failure rate than older bus. This might be expected if one considers improper installation, new components failure rate, type of construction of new switchgear, etc. As discussed below under "causes" of failures, the logicality of this observation is not consistent.

As incoming data were analyzed, it became apparent that the period reported (it was assumed that the period reported was the period of best kept records) and the age of bus did not correlate as well as expected in every case, a fallacy in the questionnaire format perhaps. Note that the older bus sample size is much larger.

Indoor and Outdoor Bus

The results of this category are summarized in Tables IX–XI below. Table XI shows an overall result of outdoor bus failure rate versus indoor bus failure rate. Outdoor bus shows a higher failure rate than indoor bus, an observation not too surprising.

Failure Duration

Failure duration results are reported in Tables XII and XIII below and categorized into repair on a round-the-clock emergency basis and repair on a normal working hour basis. This adds more meaning to the data in Table I, but would be more meaningful if repair methods were known. Urgency of repair as shown in Table XIV reveals that most repairs were made on an emergency basis. The data of these tables compare very favorable with those of the previous survey.

Type of Maintenance

Response was disappointingly low in this category and results are presented in Tables XV and XVI. The tables show results of maintenance cycles and time since last maintenance in three groups: 1) less than 12 months, 2) 12–24 months, and 3) more than 24 months. This is a very important category regarding reliability, and hopefully the next survey will produce better results.

Causes of Failures

Primary and contributing causes of failures are summarized in Tables XVII and XVIII. As might be expected inadequate maintenance is a large contributor to failures. This does not necessarily follow from the observation above on age of bus. However, defective components are a large primary cause of failures, which is logical for new installations. Correlation between the two tables below is clearly evident from the contributing cause of exposure to contaminants and the primary cause of inadequate maintenance. Exposure to contaminants, which includes dust, moisture, and chemicals, also supports the data showing outside bus with a relatively high failure rate. Inadequate maintenance was reported as the single largest primary cause of failures in the 1973 and 1974 survey [1]. This prompted the effort to survey type of maintenance in the new survey.

TABLE VII
NUMBER OF FAILURES VERSUS AGE

	ALL	INSULATED	BARE
AGE 1-10 yrs.	15	5*	10
>10 yrs.	37	23	14

* Small sample size.

TABLE VIII
FAILURE RATE (FAILURE PER UNIT-YEAR

	ALL	INSULATED	BARE
AGE 1-10 yrs.	.002298	*	.002161
>10 yrs.	.000829	.001005	.000645

* Small sample size.

TABLE IX
SWITCHGEAR BUS INSULATED

	OUTDOOR	INDOOR
Sample-Size Unit-Year	4275	20356
FAILURE	7*	19
FAILURE RATE	*	.000933

* Small sample size.

TABLE X
SWITCHGEAR BUS BARE

	OUTDOOR	INDOOR
Sample-Size Unit-Year	2750	22339
FAILURE	8	11
FAILURE RATE	.002909	.000492

TABLE XI
SWITCHGEAR BUS (OVERALL)

	OUTDOOR	INDOOR
Sample-Size Unit-Year	7825	42695
FAILURE	15	30
FAILURE RATE	.001917	.000703

TABLE XII
FAILURE DURATION: ROUND CLOCK VERSUS NORMAL HOUR
(HOURS DOWNTIME PER FAILURE)

FAILURE REPAIR URGENCY	BUS INSULATED		BUS BARE	
	MEDIAN	AVERAGE	MEDIAN	AVERAGE
ROUND CLOCK	24 hr.	87 hr.	32 hr.	39 hr.
NORMAL HOUR	240 hr.	430 hr.	24 hr.	154 hr.

TABLE XIII
FAILURE DURATION: ROUND CLOCK VERSUS NORMAL HOUR
(HOURS DOWNTOWN PER FAILURE)

	BUS INSULATED		BUS BARE	
	ROUND CLOCK	NORMAL HOUR	ROUND CLOCK	NORMAL HOUR
25 PERCENTILE	8 hr.	8 hr.	3 hr.	4 hr.
50 PERCENTILE	24 hr.	240 hr.	32 hr.	24 hr.
75 PERCENTILE	48 hr.	350 hr.	48 hr.	48 hr.

TABLE XIV
FAILURE REPAIR URGENCY

	ROUND CLOCK	NORMAL HOUR	SCHEDULE LATER
BUS INSULATED	64%	28%	8%
BUS BARE	53%	41%	6%

TABLE XV
NUMBER OF SWITCHGEAR BUS-INSULATED FAILURES VERSUS MAINTENANCE CYCLE

	LESS THAN 12 MO.	12-24 MO.	MORE THAN 24 MO.
Sample-Size (Unit-Year)	3563	8812	7253
# FAILURE	2*	13	6*
FAILURE RATE	-	.001475	

* Small sample size.

TABLE XVI
NUMBER OF SWITCHGEAR BUS BARE FAILURES VERSUS MAINTENANCE CYCLE

	LESS THAN 12 MO.	12-24 MO.	MORE THAN 24 MO.
Sample-Size (Unit-Year)	980	10,455	6312
# FAILURE	2*	12	4*
FAILURE RATE	-	.001147	-

* Small sample size.

TABLE XVII
SUSPECTED PRIMARY CAUSE OF FAILURE

BUS INSULATED	BUS BARE	
26%	17%	1. Defective Component
4%	4%	2. Improper Application
7%	9%	3. Improper Handling
7%	13%	4. Improper Installation
19%	22%	5. Inadequate Maintenance
-	18%	6. Improper Operating Procedure
11%	4%	7. Outside Agency - Personnel
26%	-	8. Outside Agency - Other
-	13%	9. Overheating

TABLE XVIII
CONTRIBUTING CAUSE TO FAILURE

BUS INSULATED	BUS BARE	
6.6%	-	1. Thermocycling
3%	8%	2. Mechanical Structure Failure
6.6%	-	3. Mechanical Damage From Foreign Source
-	15%	4. Shorting By Tools or Metal Objects
3%	-	5. Shorting By Snakes, Birds, Rodents, etc.
10%	4%	6. Malfunction of Protective Device
	4%	7. Improper Setting of Protective Device
3%	-	8. Above Normal Ambient Temperature
3%	15%	9. Exposure to Chemical or Solvents
30%	15%	10. Exposure to Moisture
10%	19%	11. Exposure to Dust or Other Contaminants
6.6%	-	12. Exposure to Non-Electrical Fire or Burning
-	8%	13. Obstruction of Ventilation
10%	4%	14. Normal Deterioration from Age
3%	4%	15. Severe Weather Condition
-	4%	16. Testing Error

TABLE XIX
FAILURE TYPE

BUS INSULATED	BUS BARE	
57%	33%	1. Short L-G
40%	60%	2. Short L-L
-	7%	3. Open
3%	-	4. Other

Failure Type

The survey results on types of failures, shown in Table XIX, show a surprisingly high percentage of failures line-to-line.

GENERAL DISCUSSION

At this point it is well to note the confidence intervals of failure rate for bare and insulated bus. Table XX shows the limits for a 90 percent confidence interval. The table illustrates the statistical limits within which 90 percent of the failures could be expected to occur.

Lack of specific details limits the integrity of some data, and as previously indicated not all categories surveyed were reported in this paper, due primarily to small sample sizes and numbers of failures. As with most surveys, accurate data combined with large response are difficult to obtain since response definitely relates to simplicity in questionnaire format. Data of the effect of maintenance on failure rate are highly desirable for obvious reasons, and effort will be made to acquire this data in the future in a meaningful and usable form.

TABLE XX
CONFIDENCE INTERVALS FOR FAILURE RATE λ

FAILURE RATE (λ) FAILURE PER UNIT-YR	INSULATED BUS >600V	BARE BUS > 600V	BARE BUS ≤ 600V
λ L *	.000779	.000958	.000521
λ	.001129	.001917	.000802
λ U *	.001569	.003488	.001203
% DEVIATION - L	31%	50%	35%
% DEVIATION - U	39%	82%	50%

* Upper and lower limits of 90 percent confidence interval for λ

APPENDIX

A. D. Patton
Texas A & M University
Department of Electrical Engineering
College Station, Texas 77843

Dear Sir:

RE: Switchgear Bus Reliability Survey for Metalclad and Metal Enclosed Switchgear

The Reliability Subcommittee of the Industrial and Commercial Power Systems Committee requests your cooperation in a survey to determine the reliability of metal-clad and metal-enclosed switchgear bus in industrial plants. The survey is a follow-up to the general reliability survey of plant equipment in 1971 and is intended to provide more meaningful data on switchgear bus. Attached for your information is a report by the subcommittee on reasons for the survey.

The results of the survey will be published in an IEEE paper and are expected to be of value to system planners and designers in the reliability evaluation of alternatives. Individual responses will be held in confidence and only summaries published.

SURVEY INSTRUCTIONS

It is hoped that the survey form is reasonably self-explanatory. Nevertheless, a sample filled-out data sheet is attached for your guidance, and some brief instructions follow. We wish to emphasize that all requested data are important, but it is realized that some of the requested information may be unknown. In such cases, simply provide the information which is known and leave the other spaces blank. We also encourage you to provide explanatory comments on any of your data as you feel appropriate. If additional data sheets are needed, please duplicate the data sheet provided.

General Data

1) It is vitally important that the period reported be given.
2) The plant climate and contamination data should be your general estimates of the requested information.

Total Population Data

1) Using the total population data block, give requested data for all buses *in service during the period reported* whether or not failures have been experienced. (Note the period reported may not exceed the age of a bus. Use separate data sheets for newer busses.)
2) It is vitally important that the number of connected circuit breakers and switches be given for each bus.

Failed Unit Data

1) List each bus failure event separately.
2) Identify the bus in each failure event by specifying the bus number as assigned in the total population data block.
3) Specify failure cause and contributing cause, where known, using the code numbers on the attached sheet.
4) Specify months since bus was last maintained.
5) Check off urgency of restoration effort.
6) Specify time in hours from onset of failure until bus was restored to service.
7) Describe component which first failed, including component material.

Our schedule dictates that responses be received no later than April 1, 1977. Your participation in this project will be greatly appreciated.

Sincerely,

A. D. Patton
Chairman, Reliability Subcommittee

SURVEY QUESTIONNAIRE

Primary Cause of Failure:

1) defective component,
2) improper application,
3) improper handling,
4) improper installation,
5) inadequate maintenance,
6) improper operating procedures,
7) outside agency–personnel,
8) outside agency–other,
9) overheating.

Contributing Cause to Failure:

1) persistent overloading,
2) transient overvoltage,
3) overvoltage,
4) thermocycling,
5) mechanical structural failure,
6) mechanical damage from foreign source,
7) shorting by tools or metal objects,
8) shorting by snakes, birds, rodents, etc.,
9) malfunction of protective device,
10) improper setting of protective device,
11) above normal ambient temperature,
12) below normal ambient temperatures,
13) exposure to chemicals or solvents,
14) exposure to moisture,
15) exposure to dust or other contaminants,
16) exposure to non-electrical fire or burning,
17) obstruction of ventilation,
18) normal deterioration from age,
19) severe weather conditions,
20) loss or deficiency of cooling medium,
21) testing error.

Comments:

REFERENCES

[1] IEEE Committee Report, "Report on reliability survey of industrial plant," *IEEE Trans. Ind. Appl.*, Mar./Apr., July/Aug., and Sept./Oct., 1974. (Part 1–Reliability of electrical equipment; Part 3–Causes and types of failures of electrical equipment, the methods of repair, and the urgency of repair; Part 5–Plant climate, atmosphere and operating schedule, the average age of electrical equipment, percent production lost, and the method of restoring electrical service after a failure; Part 6–Maintenance quality of electrical equipment.)

[2] IEEE Committee Report, "Reasons for conducting a new reliability survey on switchgear bus-insulated and switchgear bus-bare," Industrial and Commercial Power System Tech. Conf., May 1977, Conf. Rec., p. 91–95.

Working Group Procedure for Conducting an Equipment Reliability Survey

By
Power Systems Reliability Subcommittee
Power Systems Technology Committee
Industrial Power Systems Department
IEEE Industry Applications Society

Procedure I

Compiled December 8, 1980; Approved May 4, 1981

WORKING GROUP PROCEDURE FOR CONDUCTING AN EQUIPMENT RELIABILITY SURVEY

POWER SYSTEMS RELIABILITY SUBCOMMITTEE
POWER SYSTEMS TECHNOLOGY COMMITTEE
INDUSTRIAL POWER SYSTEMS DEPARTMENT
IEEE INDUSTRY APPLICATIONS SOCIETY

Scope: Conduct an equipment reliability survey of industrial plants and commercial buildings. Keep anonymous the names of those who submit data. Do not collect the equipment manufacturer's name. Publish an IEEE Working Group report. Collect data that may be included in future versions of IEEE Standard 493-1980, "IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems". This will include failures, population and unit-years, outage duration time after failure, and other information that are considered important.

Review Approval: The final IEEE Working Group report must be approved before publication by the Chairman, Power Systems Reliability Subcommittee and anyone else that he delegates. Other members of the Power Systems Reliability Subcommittee may ask to review the IEEE Working Group report before the Chairman and/or his delegates give their approval, but they do not have a veto over what is published.

Steps:

1. The Power Systems Reliability Subcommittee (PSRS) will determine the equipment category to be surveyed.

2. The PSRS Chairman will appoint a Working Group Chairman. The Working Group Chairman (WGC) will select the members of the Working Group, subject to approval by the PSRS Chairman. Usually the WG will include a WGC from a previous survey who is familiar with conducting a reliability survey. It is expected that the WGC will do the most work, including survey preparation, data collection, data analysis, and will be the coordinating author of the final report and will present the report at an IEEE technical conference. The PSRS Chairman will compile a budget and submit it to IAS for approval.

3. The WGC will compile a schedule for steps 4 through 15.

4. The WGC will review previous reliability surveys (AIEE 1962 and IEEE 1973/1974, etc.) on this equipment category, if available, and will compile a report summarizing previous survey results and why the new survey is being conducted. This report will be used in the survey and will be sent out with the survey form to the prospective participants. In some cases in the past this report has become an IEEE paper at an IEEE conference (but this is not encouraged).

5. The WGC will compile a draft form for the survey and will send it to the members of the WG. In general the new survey will be a refinement of the previous version, geared to resolving questions raised by the past surveys. He will compile a second version, third version, etc. as necessary and develop a final form incorporating comments received from Working Group members.

6. The WGC will ask all members of the PSRS: 1) if they wish to review the final form and, 2) if they wish to review the final WG report after the survey is completed. He will send copies to those who request it and should request comments back within twelve days.

7. The final form should be approved by the PSRS Chairman and those he has delegated. However, responses that take longer than two weeks may be considered "approval by default".

8. The WGC will have the material for the survey printed (cover letter on IEEE stationery, form & definitions, reasons for survey). He will obtain the mailing list from the Chairman, Mailing List Working Group. He will review the list and augment it if appropriate. The WGC will buy postage stamps and send the survey material out for the survey. A return envelope and postage will be included and a requested return date will also be included. The WGC will keep track of negative, moved, or deceased responses for feedback to the Mailing List Chairman.

9. A follow up letter will be sent out by the WG Chairman to all participants about 8 weeks later. This always brings in additional responses.

10. An oral pep talk (3 minutes long) should be given by WGC during a technical session at the I & CPS Conference (if the timing is convenient).

11. After the "cut off" date, the WGC will analyse and tabulate the results from the survey. (An attempt should be made to contact respondents for clarification of incomplete or inconsistent data). They will be sent to the WG members for comments and suggestions for additional analysis and for what should go into the WG report.

12. The WGC will compile a first draft WG report and will send a copy to the members for comments. A second draft, third draft will be compiled as needed. A final WG report will be compiled.

13. The final WG report will be sent to the PSRS Chairman and those he has delegated for approval. Fourteen days will be allowed for their review. The final WG report will also be sent to those PSRS members who have requested it in step 6, and comments should be requested back within twelve days.

14. The WG Chairman will have the approved final WG report typed on modelpaper for presentation at an IEEE technical conference. Only those who have contributed as Working Group members, or by commenting on the survey or report drafts should be listed as authors; the WGC will obtain written approval from each co-author to use their names on the report. Approval of the final report by those who request it to review should be adequate approval to use names. A copy of this paper should be sent to all members of the PSRS; written discussions should be invited back from them. Other solicitations for discussions are also encouraged as deemed appropriate by the WGC or the PSRS Chairman.

15. The WG Chairman should present the final WG report at the IEEE Conference. An alternate from the WG should be designated, by the WGC, to present the paper in his absence.

It is believed that the total time cycle for steps 1 through 15 is about two years.

Charles R. Heising

Charles R. Heising
Secretary
Power Systems Reliability Subcommittee

CRH:sk

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

INDUSTRY APPLICATIONS SOCIETY

TYPICAL MAJOR MILESTONE SCHEDULE
for
EQUIPMENT RELIABILITY SURVEYS

YEAR 1:

1. May/June (I&CPS Conference) PSRSC Chairman appoints WG Chairman.
2. October (IAS Conference) WG Chairman presents first draft of survey form to WG.
3. November/December. WG Chairman finalizes survey form and obtains approval from PSRSC Chairman.

YEAR 2:

4. January/February. WG Chairman mails survey form to industries.
5. March/April. WG Chairman mails follow-up letter to industries.
6. May/June (I&CPS Conference) WG Chairman presents a pep talk to Conference, outlining reasons for survey.
7. August/September. WG Chairman evaluates data received; compiles first draft of report.
8. September/October (IAS Conference) WG Chairman reviews first draft of paper with members of WG and PSRSC.
9. November/December. WG Chairman prepares number of drafts required to satisfy need of WG.

YEAR 3:

10. January. WG Chairman sends final draft to PSRSC Chairman for approval.
11. February. WG Chairman prepares final manuscript and transmits for publication in I&CPS Conference record.
12. May/June (I&CPS Conference) WG Chairman presents results of survey at Conference.

Prepared by:

Philip E. Gannon, Chairman

Report of Transformer Reliability Survey—Industrial Plants and Commercial Buildings

By
James W. Aquilino

IEEE Transactions on Industry Applications
September/October 1983, pp. 858–866

Report of Transformer Reliability Survey—Industrial Plants and Commercial Buildings

JAMES W. AQUILINO, MEMBER, IEEE

***Abstract*—The Power Systems Reliability Subcommittee of the IEEE Industry Applications Society has been conducting surveys of the reliability of electrical equipment in industrial and commercial power systems. A previous survey published in 1973 and 1974 [1] included data on the reliability of transformers. Some of the questions raised by the previous results, together with a general need for updated data, prompted a new survey which was conducted in 1979. The results of that survey are presented in this paper.**

INTRODUCTION

ACCURATE reliability data on transformers, together with similar data on other types of electrical equipment, are necessary for evaluating power system reliability. Information of this type is often the only means of showing economic justification for spares, redundancy, or improved maintenance programs. The purpose of this 1979 transformer reliability survey of industrial plants and commercial buildings was to improve upon the results of the previous survey published in 1973-1974 [1] by answering some of the questions raised and eliminating some of the controversy created. The major reasons for conducting the new survey were outlined in a paper presented at the 1979 Industrial and Commercial Power Systems Technical Conference [2].

The most controversial items in the previous survey concerned the average outage duration time after a transformer failure in relation to the failure restoration method. Another item which raised questions was the comparatively high failure rate for rectifier transformers. The 1979 survey form was condensed considerably from the 1973-1974 version. Most of the items found to be of little significance in the past have been omitted. The remaining survey items are aimed at factors believed to have the most influence on the important transformer reliability and availability parameters.

Another major consideration in preparing the new survey form was simplicity. This was intended to enable the respondent to reply with minimal effort, thereby assuring maximum possible response. Obviously, the condensation could only be carried to a certain extent before the survey results would become so general that they would be of little practical value.

Results of the 1979 transformer survey are presented in this paper in tabular form. The discussion which follows under *Survey Results* attempts to expand upon some of the more significant survey data obtained. In any survey of this type there will undoubtedly be some new questions raised and also some old questions and controversies left unresolved. We feel, however, that this data will be of considerable value to system planners, designers, and users.

Paper IPSD 80-7, approved by the Power Systems Technologies Committee of the IEEE Industry Applications Society for presentation at the 1980 Industrial and Commercial Power Systems Conference, Houston, TX, May 12-15. Manuscript released for publication February 2, 1981.

The author was with Northrop Corporation, 100 Morse Street, Norwood, MA 02062. He is now with General Radio (GenRad), 170 Tracer Lane, Waltham, MA 02154.

SURVEY FORM

The form used for the 1979 survey is shown in the Appendix. As mentioned before, the Total Population form was condensed to include data relating specifically to transformer reliability. Important influencing factors were rating, voltage, age, and maintenance. However, reporting the response to maintenance quality is difficult. The 1973-1974 survey asked the respondent to give his or her opinion of the maintenance quality as excellent, fair, poor, or none. It is very difficult to be completely objective in responding to this type of question. The new survey, therefore, asked for a brief description of the extent of maintenance performed, the idea being to enable the reader to judge for himself the benefits derived from a particular maintenance procedure. The failed unit data requested is basically the same as that in the previous survey. The most important categories here are the causes of failure, the restoration method, restoration urgency, duration of failure, and age at time of failure.

SURVEY RESPONSE

The response to the survey is summarized in Tables I and II. Responses were received from 25 different companies, and in many cases several locations within the companies were reported. Various types of industrial and commercial facilities are represented including chemical and petro-chemical plants, steel mills, paper mills, manufacturing plants, and hospitals, to name a few. Similar data from the 1973-1974 survey are shown in Table III for comparative purposes. A summarized comparison between the two survey results appears in Table IV. Direct comparisons cannot be made in some instances because of changes made in the sub-classes. For example, the new survey broke the ratings down into two groups, units 300-10 000 kVA and those greater than 10 000 kVA. The ratings in the previous survey were 300-750 kVA, 751-2 499 kVA, and 2 500 kVA and up.

One of the reasons for conducting this new survey was the need for reliability data on arc-furnace transformers. Unfortunately, the response to this category was very poor. The sample size reported was too small to obtain reliable results, therefore, the arc-furnace data were omitted. Hopefully, the response will improve in subsequent surveys. The response to the latest survey did improve over the 1973-

TABLE I
POWER TRANSFORMERS 1979 SURVEY

Type	Number of Units	Unit-Years	Number of Failures	Failure Rate Failures/ Unit-Year	Average Repair Time (Hours)	Average Replacement Time (Hours)
All liquid filled	1814	17 996	111	0.0062	356.1 N: 60 F[2]	85.1 N: 39 F[2]
Liquid 300–10 000 kVA	1750	17 410	102	0.0059	297.4 N: 56 F[2]	79.3 N: 37 F[2]
Liquid >10 000 kVA	64	586	9	0.0153	1178.5[1] N: 4 F[2]	192[1] N: 2 F[2]
Dry 300–10 000	159	1700	1[1]	0.0006[1]	6[1] N: 1 F[2]	– N: 0 F[2]

[1] Small sample size–less than eight failures.
[2] F is failures.

TABLE II
RECTIFIER TRANSFORMERS 1979 SURVEY

Type	Number of Units	Unit-Years	Number of Failures	Failure Rate Failures/ Unit-Year	Average Repair Time (Hours)	Average Replacement Time (Hours)
All liquid filled	85	841	16	0.0190	2316 N: 8 F[2]	41.4 N: 8 F[2]
Liquid 300–10 000 kVA	61	644	10	0.0153	1664[1] N: 3 F[2]	38.7[1] N: 7 F[2]
Liquid >10 000 kVA	24	197	6[1]	0.0303[1]	2707.2[1] N: 5 F[2]	60[1] N: 1 F[2]

[1] Small sample size–less than eight failures.
[2] F is failures.

TABLE III
ALL TRANSFORMERS[1]

Number of Plants in Sample Size	Sample Size Unit-Years	Number of Failures Reported	Industry		Failure Rate-Failures per Unit-Year	Industry Average	Actual Hours Downtime/Failure Minimum Plant Average	Median Plant Average	Maximum Plant Average
33	15,210	63	All..........	Liquid Filled - All.............	0.0041	529.0	2.0	219.	3744.
30	13,210	39	"	601-15,000 volts-All Sizes....	0.0030	174.	2.0	49.	840.
12	3,002	11	"	300-750 kVA................	0.0037	61.0	4.5	10.7	336.
18	6,040	15	"	751-2,499 kVA..............	0.0025	217.	2.0	64.0	840.
11	4,036	13	"	2,500 kVA & up..............	0.0032	216.	24.0	60.0	403.
12	1,848	24	"	Above 15,000 volts...........	0.0130	1076.	12.8	1260.	3744.
16	4,937	18	"	Dry Type; 0-15,000 volts........	0.0036	153.	0.5	28.	720.
3	672	20	"	Rectifier; Above 600 volts......	0.0298	380.	24.0	80.	867.
14	8,598	43	Chemical.....	Liquid Filled - All.............	0.0050	338.	8.0	168.	1800.
12	6,838	24	"	601-15,000 volts-All Sizes....	0.0035	52.3	8.0	48.5	336.
7	3,274	10	"	300-750 kVA................	0.0031	19.3	3.0	8.0	120.
9	1,601	19	"	Above 15,000 volts...........	0.0119	670.	12.8	708.	3600.
2	662	16	"	Rectifier; Above 600 volts......	0.0242	425.	80.0	474.	867.
3	2,512	14	Petroleum....	Liquid Filled - All.............	0.0056	843.	4.5	591.	1178.
3	2,334	10	"	601-15,000 volts-All Sizes....	0.0043	244.	4.5	204.	403.

[1] From IEEE Survey published in 1973–1974 [1].

TABLE IV
ALL TRANSFORMERS[1]

	Sample Size Unit-Years	Number of Failures	Type	Failure Rate Failures/ Unit-Year	Average Hours Downtime/ Failure
1979 Survey	17996	111	Power-Liquid Filled	0.0062	249.3
	1700	1[2]	Power-Dry	0.0006[2]	6
	841	16	Rectifier	0.0190	1178.7
1973/74 Survey	15210	63	Liquid Filled	0.0041	529
	4937	18	Dry	0.0036	153
	672	20	Rectifier	0.0298	380

[1] Comparison of 1979 and 1973-1974 surveys.
[2] Small sample size-less than eight failures.

TABLE V
FAILURE RATE VERSUS AGE

Type	Age[1] (Yrs)	Number of Units	Sample Size Unit-Years	Number of Failures[2]	Failure Rate Failures/ Unit-Year
		Power Transformers			
Liquid					
300-10 000 kVA	1-10	638	2625.5	19	0.0072
300-10 000 kVA	11-25	715	8846.5	47	0.0053
300-10 000 kVA	>25	397	5938.0	36	0.0060
Liquid					
>10 000 kVA	1-10	27	144.0	0[3]	
>10 000 kVA	11-25	28	283.5	7[3]	0.0246[3]
>10 000 kVA	>25	9	158.0	2[3]	0.0126[3]

[1] Age is the age at end of reporting period.
[2] Relay or tap changer faults were not considered in calculations for failure rates or repair and replacement times.
[3] Small sample size-less than eight failures.

1974 survey as seen by comparing the total number of unit-years for both the power and rectifier transformers. Not too surprisingly, the largest sample size reported occurred among the power transformers 300-10 000 kVA which totaled 17410 unit-years.

SURVEY RESULTS

In Table IV it is clear that the results from the largest category, liquid filled power transformers, compared favorably between the 1973-1974 and 1979 surveys. This table also confirms the high failure rates for rectifier transformers. Before a further discussion on the results of the survey, in general, it would be worthwhile to note how the data compared with the controversial items in the previous survey.

The total number of hours (130 h) to replace a failed transformer with a spare appeared in Table 48 of the results of the 1973-1974 survey, under units 601-15 000 volts requiring a round-the-clock all out effort, and was felt by many to be too high. Units that were repaired showed an average outage time of 342 h. The new survey shows a considerable variation among power transformers depending upon size. The higher voltage units, reported in Table 49 of the results published in the 1973-1974 survey, showed an average repair time of 1842 h. This difference could be due to several factors, such as the transportation and handling problems associated with the larger units and the greater likelihood of having spares for the smaller units on hand at the site.

The results of the new survey confirmed the long replacement time after a transformer failure. The much longer times needed to repair a failed transformer than to replace it with a spare were also confirmed. The new survey also confirmed the fact that the failure rates for rectifier transformers are much higher than those for the other transformer categories. This may be due to severe duties or the environments to which they are subjected.

AGE

Table V contains data broken down into three age groups. The failure rates for power transformers 300-10 000 kVA were approximately equal in all three age groups. The slightly higher failure rates for the units aged 1-10 years, and greater than 25 years, can probably be attributed to the infant mortality rate and units approaching end of life, respectively.

RESTORATION METHOD

Tables I and II also include data on restoration times versus restoration method. The data clearly indicate that the restoration of a unit to service by repair rather than replacement results in a much longer outage duration in all cases. This compares favorably with the previous survey which showed

TABLE VI
FAILURE INITIATING CAUSE

All Power Transformers	No. of Failures[1]	Percentage
Transient overvoltage disturbance (switching surges, arcing ground fault, etc...)	18	16.4
Overheating	3	2.7
Winding insulation breakdown	32	29.1
Insulating bushing breakdown	15	13.6
Other insulation breakdown	6	5.4
Mechanical breaking, cracking, loosening, abrading or deforming of static or structural parts	8	7.3
Mechanical burnout, friction or seizing of moving parts.	3	2.7
Mechanically caused damage from foreign source (digging, vehicular accident, etc.)	3	2.7
Shorting by tools or other metal objects	1	0.9
Shorting by birds, snakes, rodents, etc.	3	2.7
Malfunction of protective relay control device or auxiliary device	5	4.5
Improper operating procedure	4	3.6
Loose connection or termination	8	7.3
Others	1	0.9
Continuous overvoltage	0	0
Low voltage	0	0
Low frequency	0	0
	110	

[1] Failure initiating cause not specified for two failures.

TABLE VII
FAILURE CONTRIBUTING CAUSE

All Power Transformers	No. of Failures[1]	Percentage
Persistent overloading	1	1.1
Abnormal temperature	5	5.5
Exposure to aggressive chemicals, solvents, dusts, moisture or other contaminants	13	14.4
Normal deterioration from age	12	13.3
Severe wind, rain, snow, sleet or other weather conditions	4	4.4
Lack of protective device	2	2.2
Malfunction of protective device	7	7.8
Loss, deficiency, contamination, or degradation of oil or other cooling medium	9	10.0
Improper operating procedure or testing error	3	3.3
Inadequate maintenance	7	7.8
Others	27	30.0
Exposure to non-electrical fire or burning	0	0
Obstruction of ventilation by foreign object or material	0	0
Improper setting of protective device	0	0
Inadequate protective device	0	0
	90	

[1] Failure contributing cause not specified for 22 failures.

TABLE VIII
SUSPECTED FAILURE RESPONSIBILITY

All Power Transformers	Number of Failures[1]	Percentage
Manufacturer defective component or improper assembly	32	33.3
Transportation to site, improper handling	1	1
Application engineering, improper application	3	3.1
Inadequate installation and testing prior to start-up	6	6.3
Inadequate maintenance	25	26.0
Inadequate operating procedures	4	4.2
Outside agency–personnel	3	3.1
Outside agency–others	6	6.3
Others	16	16.7
	96	

[1] Suspected failure responsibility not specified for 16 failures.

repair times considerably longer than replacement times. Despite this fact, in most cases, a larger number of units was restored to service by repair. Results such as these show the obvious benefits in having spares at the site or readily available. The data may also help system planners and users determine the economic feasibility of purchasing spares. In computing the average repair and replacement times, those instances in which the repair or replacement was deferred were excluded to avoid distorting the averages. The averages shown represent only those cases where restoration was begun immediately.

FAILURE CAUSE

Tables VI–XI summarize the causes which initiate and contribute to the failure and the suspected failure responsibility for both power and rectifier transformers. Tables VI and IX show large percentages of failures initiated by some type of insulation breakdown or transient overvoltages. Table IX, however, shows a surprisingly large percentage of rectifier transformer failures initiated by mechanical causes.

Tables VII and X, which show the failure contributing causes, compare well with the 1973-1974 survey results. Normal deterioration from age contributed to a large number of both power and rectifier transformer failures. As in the past, Table VIII shows that respondents believed that manufacturer defects and inadequate maintenance were responsible for the greatest numbers of failures of power transformers. Table XI shows inadequate operating procedure was also a significant cause of failures of rectifier transformers.

MAINTENANCE CYCLE AND EXTENT OF MAINTENANCE

The large percentage of failures which resulted from inadequate maintenance shows the importance of accurate data on the extent and frequency of the maintenance performed. The latest survey attempted to obtain this data in a simple form. The response did not lend itself to reporting in tabular form. Maintenance information continues to be the most difficult to obtain in useful form, not only for transformers, but for all other equipment that have been surveyed as well. Hopefully in the future, we will be able to devise a method of obtaining this data and reporting it in a manner that will enable system users to establish effective preventive maintenance programs.

TYPE OF FAILURE

The 1979 survey limited the choices of failure type to "winding" and "other" (Tables XII and XIII). About half of the failures occurred on transformer windings.

TABLE IX
FAILURE INITIATING CAUSE

All Rectifier Transformers	Number of Failures[1]	Percentage
Transient overvoltage disturbance (lightning, switching surges, arcing ground fault, etc.).	2	13.3
Overheating	1	6.6
Winding insulation breakdown	2	13.3
Insulation bushing breakdown	1	6.6
Other insulation breakdown	3	20
Mechanical breaking, cracking, loosening, abrading or deforming of static or structural parts	3	20
Mechanical burnout, friction or seizing of moving parts	2	13.3
Loose connection or termination	1	6.6
Continuous overvoltage	0	0
Mechanically caused damage from foreign source (digging, vehicular accident, etc.)	0	0
Shorting by tools or other metal objects	0	0
Shorting by birds, snakes, rodents, etc.	0	0
Malfunction of protective relay control device or auxiliary device	0	0
Low voltage	0	0
Low frequency	0	0
Improper operating procedure	0	0
Other	0	0
	15	

[1] Failure initiating cause not specified for 1 failure.

TABLE X
FAILURE CONTRIBUTING CAUSE

All Rectifier Transformers	No. of Failures[1]	Percentage
Abnormal temperature	1	7.1
Exposure to aggressive chemicals, solvents dusts, moisture or other contaminants	1	7.1
Normal deterioration from age	4	28.6
Inadequate protective device	1	7.1
Loss, deficiency, contamination or degradation of oil or other cooling medium	3	21.4
Inadequate maintenance	3	21.4
Others	1	7.1
Persistent overloading	0	0
Exposure to non-electrical fire or burning	0	0
Obstruction of ventilation by foreign object or material	0	0
Severe wind, rain, snow, sleet or other weather conditions	0	0
Improper setting of protective device	0	0
Lack of protective device	0	0
Malfunction of protective device	0	0
Improper operating procedure or testing error	0	0
	14	

[1] Failure contributing cause not specified for two failures.

FAILURE CHARACTERISTIC

As would be expected, Tables XIV and XV show that about 3/4 of transformer failures resulted in removal from service by automatic protective devices, however, the percentage requiring manual removal was significant. Increasing use of transformer oil or gas analysis could be a factor here. This would enable detection of incipient faults in their early stages, allowing manual removal before a large scale failure occurs.

TABLE XI
SUSPECTED FAILURE RESPONSIBILITY

All Rectifier Transformers	Number of Failures	Percentage
Manufacturer–defective component or improper assembly	5	31.2
Application engineering–improper application	2	12.5
Inadequate maintenance	2	12.5
Inadequate operating procedures	5	31.2
Others	2	12.5
Transportation to site–improper handling	0	0
Inadequate installation and testing prior to startup	0	0
Outside agency–personnel	0	0
Outside agency–others	0	0
	16	

TABLE XII
TYPE OF FAILURE

Type of Failure	Power Transformers Number of Failures	Percentage
Winding	59	53
Others	53	47

TABLE XIII
TYPE OF FAILURE

Type of Failure	Rectifier Transformers Number of Failures	Percentage
Winding	8	50
Others	8	50

TABLE XIV
FAILURE CHARACTERISTICS

Failure Characteristic	Power Transformers Number of Failures	Percentage
Automatic removal by protective device	83	75
Partial failure reducing capacity	5	5
Manual removal	23	20

TABLE XV
FAILURE CHARACTERISTIC

Failure Characteristic	Rectifier Transformers Number of Failures	Percentage
Automatic removal by protective device	11	69
Partial failure reducing capacity	0	0
Manual removal	5	31

VOLTAGE

Table XVI shows the failure rate for liquid filled power transformers broken down by voltage rating. From Table XVI it is evident that the failure rates for 600-15 000 volt transformers are less than those for the higher voltage units in both

TABLE XVI
FAILURE RATE VERSUS VOLTAGE

Power Transformers					
Type	Voltage (kV)	Number of Units	Sample Size Unit-Years	Number of Failures	Failure Rate Failures/Unit-Year
Liquid 300–10 000 kVA	.6–15	1626	15775	82	0.0052
Liquid 300–10 000 kVA	>15	124	1637	18	0.0110
Liquid >10 000 kVA	>15	52	490	9	0.0184

TABLE XVII
FAILURE RATE VERSUS VOLTAGE

Rectifier Transformers					
Type	Voltage (kV)	Number of Units	Sample Size Unit-Years	Number of Failures	Failure Rate Failures/Unit-Year
All Liquid	.6–15	65	745	15	0.0201

size categories. The small sample sizes in several categories in Table XVII make it impossible to draw any definite conclusions on the effect of voltage on the failure rates of rectifier transformers.

CONCLUSION

The purpose of this survey was to update the results of the 1973–1974 survey and to clarify some of the issues raised by those results. In general, the data obtained in the latest survey confirm the previous results.

Only that data from which meaningful results could be obtained were included in this report. Obviously more information was requested in the survey than discussed in the previous sections. The remaining data were eliminated either because the sample sizes were too small, because analysis showed it to have little or no influence on transformer reliability, or because it could not be reported in a meaningful way.

APPENDIX

December 15, 1978

Subject: *Reliability Survey for Power, Rectifier, and Arc-Furnace Transformers*

Dear Sir:

The Power System Reliability Subcommittee of the Industrial and Commercial Power Systems Committee requests your cooperation in a survey to determine the reliability of power, rectifier, and arc-furnace transformers in industrial plants. This survey is part of a program to update the information obtained in our 1971 general reliability survey of plant equipment and to provide additional information on rectifier and arc-furnace transformers.

The results of this survey will be published in an IEEE paper. The information obtained is expected to be of value to system planners, designers, and users in the reliability evaluation of various alternatives. Individual responses will be held in confidence and only summaries published.

SURVEY INSTRUCTIONS

Definitions, brief instructions, and sample survey forms (Figs. 1-2) are provided for guidance. We wish to emphasize that all requested data is important, but it is also realized that some of the information requested may be unknown. In such cases, simply provide the information that is known, and leave the other spaces blank. If additional survey forms are needed, please duplicate the forms provided.

Definitions

1) Failure: A failure is any trouble with a power system component that causes any of the following to occur:

a) partial or complete shutdown, or below standard plant operation,
b) unacceptable performance of user's equipment,
c) operation of the electrical protective relaying or emergency operation of the plant electrical system,
d) de-energization of any electric circuit or equipment.

2) Failure Duration: Duration of a failure or repair time of a failed component is the clock hours from the time of the occurrence of the failure to the time when the component is restored to service, either by repair of the component or by substitution with a spare component. It includes time for diagnosing the trouble, locating the failed component, waiting for parts, repairing or replacing, and restoring the component to service. *It is not the time required to restore service to a load by putting alternate circuits into operation.*

Company Name and Plant: ______________________________

Location: ______________________________

Industry Type: ______________________________

Period Reported: From: Month ______________ Year ________

To: Month ______________ Year ________

TOTAL POPULATION: (List each transformer by number on a separate line.)

Transformer Number	Type 1/	Subclass Type 1/	Age at End of Period (Years)	Location 1/	Number of Phases	Primary Voltage Class (kV)	Rating 1/	Maintenance Cycle (Months)	Extent of Maintenance

1/ Use code from attached sheets.

Fig. 1. Reliability survey for power, rectifier, and arc-furnace transformers.

						Type of Failure 2/		Restoration Method 2/		Restoration Urgency 2/				
Transformer Number	Age at Time of Failure (Years)	Failure Initiating Cause 1/	Failure Contributing Cause 1/	Suspected Failure Responsibility 1/	Failure Characteristic 1/	Winding	Other	Repair Failed Component	Replace with Spare	Round the Clock Emergency Basis	Normal Work Hours	Scheduled Later	Duration of Outage (Hours)	Description of Failed Component

1/ Use code from attached sheets.
2/ Check applicable box.

Fig. 2. Failed Unit Data: Use transformer number from total population form.

General Data

1) It is vitally important that the period being reported be given.
2) Indicate the general type of industry involved at the plant being reported, such as auto, cement, chemical, metalworking, petroleum, pulp and paper, textile, etc.

Total Population Data

1) Using the Total Population data block, give the requested data for ***all power, rectifier, and arc-furnace transformers in service during the period reported whether or not failures have been experienced.*** Data should be reported on only those transformers used on a continuous basis. Transformers which are de-energized for substantial periods of time should not be included.
2) The age is the number of years from the time of installation to the end of the period reported under General Data.
3) Give a brief description of the extent of maintenance.

Failed Unit Data

1) List each failure separately.
2) Transformer Number for each failure is the Transformer Number used on the Total Population form.
3) Specify the age of the transformer at the time of failure.
4) Specify the failure initiating cause, contributing cause, and suspected failure responsibility using the code numbers on the attached sheets.
5) Check the restoration urgency.
6) Specify the time in hours from the onset of the failure until the transformer was restored to service.
7) Describe briefly the component that failed, including the component material.

Your participation in this survey will be greatly appreciated.

Sincerely,

J. W. Aquilino
Working Group Chairman

CODE NUMBERS TO BE USED WITH TOTAL POPULATION FORM

Transformer Type

1) Power
2) Rectifier
3) Arc-Furnace

Subclass Type

1) Liquid
2) Dry

Location

1) Indoor
2) Outdoor

Rating

1) 300–10 000 kVA
2) >10 000 kVA

CODE NUMBERS TO BE USED WITH FAILED UNIT DATA FORM

Failure Initiating Cause

1) Transient overvoltage disturbance (lightning, switching surges, arcing ground fault, etc.).
2) Continuous overvoltage.
3) Overheating.
4) Winding insulation breakdown.
5) Insulating bushing breakdown.
6) Other insulation breakdown.
7) Mechanical breaking, cracking, loosening, abrading, or deforming of static or structural parts.
8) Mechanical burnout, friction, or seizing of moving parts.
9) Mechanically caused damage from foreign source (digging, vehicular accident, etc.).
10) Shorting by tools or other metal objects.
11) Shorting by birds, snakes, rodents, etc.
12) Malfunction of protective relay control device or auxiliary device.
13) Low voltage.
14) Low frequency.
15) Improper operating procedure.
16) Loose connection or termination.
17) Others.

Failure Contributing Cause

1) Persistent overloading.
2) Abnormal temperature.
3) Exposure to aggressive chemicals, solvents, dusts, moisture, or other contaminants.
4) Exposure to nonelectrical fire or burning.
5) Obstruction of ventilation by foreign object or material.
6) Normal deterioration from age.
7) Severe wind, rain, snow, sleet, or other weather conditions.
8) Improper setting of protective device.
9) Lack of protective device.
10) Inadequate protective device.
11) Malfunction of protective device.
12) Loss, deficiency, contamination, or degradation of oil or other cooling medium.
13) Improper operating procedure or testing error.
14) Inadequate maintenance.
15) Others.

Suspected Failure Responsibility

1) Manufacturer-defective component or improper assembly.

2) Transportation to site-improper handling.
3) Application engineering-improper application.
4) Inadequate installation and testing prior to startup.
5) Inadequate maintenance.
6) Inadequate operating procedures.
7) Outside agency-personnel.
8) Outside agency-others.
9) Others.

Failure Characteristic

1) Automatic removal by protective device.
2) Partial failure reducing capacity.
3) Manual removal.

REFERENCES

[1] "Report on reliability survey of industrial plants," *IEEE Trans. Ind. Appl.*, Mar./Apr., July/Aug., and Sept./Oct., (Parts I–VI), 1974.

[2] "Reasons for conducting a new reliability survey on power, rectifier and arc-furnace transformers," in the *Ind. Comm. Power Syst. Tech. Conf.*, May 1979, pp. 70–75.

James W. Aquilino (M'76) was born in Arlington, MA, in 1949. He received the B.S.E.E. degree from Northeastern University, Boston, MA, in 1972.

After a brief period working in the field of special electronic instrumentation, he joined the Factory Mutual Engineering Association as a Loss Prevention Engineer specializing in electrical equipment and electric utility generating plants. He later joined the electrical section of the Factory Mutual Research Corporation, Boiler and Machinery Standards Department, where his duties included the preparation of standards for the protection and maintenance of electrical equipment. While employed at Factory Mutual, he represented the company as a member of the National Fire Protection Association on NFPA No. 75, Electronic Data Processing, on NEC Code Panels Nos. 11 and 23, and as an alternate on Panel No. 4. He then joined GenRad, Inc., in Concord, MA, as a Senior Facilities Engineer in the Corporate Plant Engineering Department where his responsibilities included plant electrical engineering, utilities monitoring, energy conservation, and preventive maintenance, among others. He was employed as a Plant Engineer at Northrop Corporation's Precision Products Division in Norwood, MA. He has since returned to GenRad.

Mr. Aquilino is a member of the IEEE Industry Applications Society Industrial Power Systems Department, Power Systems Support Committee, and the Power System Reliability Subcommittee. He served as the Chairman of the Working Group on Transformer Reliability. He is a Registered Professional Engineer in the State of Massachusetts.

Report of Large Motor Reliability Survey of Industrial and Commercial Installations Parts I, II, and III

By
P. O'Donnell

Motor Reliability Working Group
Power Systems Reliability Subcommittee
Power Systems Engineering Committee
Industrial and Commercial Power Systems Department
IEEE Industry Applications Society

IEEE Transactions on Industry Applications
Parts I and II, July/August 1985, pp. 853–872
Part III, January/February 1987, pp. 153–158

Report of Large Motor Reliability Survey of Industrial and Commercial Installations, Part I

MOTOR RELIABILITY WORKING GROUP
POWER SYSTEMS RELIABILITY SUBCOMMITTEE
POWER SYSTEMS ENGINEERING COMMITTEE
INDUSTRIAL AND COMMERCIAL POWER SYSTEMS DEPARTMENT
IEEE INDUSTRY APPLICATIONS SOCIETY

***Abstract*—The Power Systems Reliability Subcommittee of the IEEE Industry Applications Society recently initiated a survey of the reliability of large motors in industrial and commercial installations in keeping with its commitment to support or update results of the survey published in 1973 and 1974. Moreover, the new survey has emphasized and expanded on one type of electrical equipment only. The previous survey results were heavily biased by one class of motors in the motor category and contained some results that appeared unreasonable and were considered questionable. The results of this new survey are presented here and intended to expand failure data to additional influencing categories and at the same time be oriented to the more common types in use today. A restriction to a lower limit in size also distinguishes the results to motors in relatively critical applications. A further explanation of the reasons for this survey and intended results is presented in a subcommittee report included for reference in the Appendix.**

INTRODUCTION

THE RESULTS of the 1982 survey on the reliability of motors in industrial and commercial installations are summarized in Tables I–XIX. The data obtained allowed the various categories to be shown here which provide failure data on a more expanded and detailed basis, for the most part, than was presented in the 1973/1974 survey results. Also comparisons are made with the previous survey where results are of similar format.

To focus on motors that are of a critical nature, where reliability is most important, this survey differs from the other in that only motors larger than 200 hp are considered. In addition, to present data on motors most commonly manufactured and used today and to avoid distorted failure data from old motors that are expected to have high failure rates, this survey has limited the age of motors to no more than 15 years.

A brief discussion is included for each table identifying significant points and results of the survey. The intent of this working group report is to present these results as updated experience in industry applications, and the drawing of definite conclusions is left to the reader.

Paper IPSD 83-12, approved by the Power Systems Technologies Committee of the IEEE Industry Applications Society for presentation at the 1984 Industrial and Commercial Power Systems Conference, Atlanta, GA, May 7–10, 1984. Manuscript released for publication May 7, 1984.

Members of IEEE Motor Reliability Working Group

R. N. Bell is with E.I. du Pont de Nemours & Company, Engineering Department, Louviers Building, L5231, Wilmington, DE, 19898.

D. W. McWilliams was with the Gates Rubber Company, 999 South Broadway, Denver, CO 80217. He is now deceased.

P. O'Donnell, *Coordinating Author*, is with El Paso Natural Gas Company, Tex & Stanton Box 1492, El Paso, TX 79978.

C. Singh is with Texas A&M University, Department of Electrical Engineering, College Station, TX 77843.

S. J. Wells is with Union Carbide Corporation, P.O. Box 50, Hahnville, LA 70057.

SURVEY RESPONSE

The cover letter and questionaire form used in the survey are included in the Appendix. The form is specifically oriented to motors greater than 200 hp in size and no older than 15 years. As in other surveys succeeding the 1973 overall survey, this form is simplified into two sections: total population data and failure data.

Although the response was inadequate to identify a substantial number of industry types, the number of companies and plants identified was encouraging and the overall response was considered a success. Total population is less in this survey than in the 1973 survey, but this was anticipated due to the restriction on age and size. However, the total number of plants in the new survey is greater which adds credibility to the data as being representative of industry applications. The following list summarizes the magnitude of the response:

number of plants	75
number of companies	33
number of motors	1141
total population (unit years)	5085.0
total failures	360.

Some respondents did not submit data for every category evidenced by the comment "not specified" in the tables. Where response was insufficient to identify the motor and/or period reported the response was not used. As in previous survey reports, this report maintains the standard for credibility of failure rates by identifying categories that contain an insufficient number of failures to be representative.

SURVEY RESULTS

Summary

Table I summarizes the results in types of motors and voltage classes in similar fashion to the previous survey summary table. The previous data have been rearranged for comparison and presented here as Table II. In the new survey there was not enough response to separate the petroleum industry and chemical industry or to separate out other industry types and still show meaningful results.

TABLE I
OVERALL SUMMARY—LARGE MOTORS

Number of Plants in Sample Size	Sample Size (Unit Yr)	Number of Failures Reported	Industry	Equipment Subclass	Failure Rate (Failures/ Unit Yr)	Average Hours Downtime/ Failure	Median Hours Downtime/ Failure
75	5085.0	360	all	all	0.0708	69.3	16.0
				induction			
33	1080.3	89	all	0–1000 V	0.0824	42.5	12.0
52	2844.4	203	all	1001–5000 V	0.0714	75.1	12.0
5	78.1	2*	all	5001–15 000 V	*	*	*
1	13.5	—	all	not specified	—	—	—
				synchronous			
19	459.3	35	all	1001–5000 V	0.0762	78.9	16.0
2	29.5	3*	all	5001–15 000 V	*	*	*
				wound rotor			
5	137.0	10	all	0–1000 V	0.0730	*	*
9	251.1	8	all	1001–5000 V	0.0319	*	*
2	39.0	4*	all	5001–15 000 V	*	*	*
				direct current			
5	122.7	6*	all	0–1000 V	*	*	*
1	30.0	—	—	1001–5000 V	—	—	—
				induction			
11	484.3	39	petrochemical	0–1000 V	0.0805	88.3	40.0
28	1349.0	108	petrochemical	1001–5000 V	0.0801	109.4	48.0
2	10.3	1*	petrochemical	5001–15 000 V	*	—	—
				synchronous			
7	73.0	8	petrochemical	1001–5000 V	0.1096	72	16.0
				wound rotor			
2	20.8	4*	petrochemical	0–1000 V	*	—	—
3	17.6	3*	petrochemical	1001–5000 V	*	—	—

* Small sample size.

TABLE II
1973 OVERALL SUMMARY—MOTORS

Number of Plants in Sample Size	Sample Size (Unit Yr)	Number of Failures Reported	Industry	Equipment Subclass	Failure Rate (Failures/ Unit Yr)	Average Hours Downtime/ Failure	Median Hours Downtime/ Failure
—	42 463	561	all	all	0.0132	111.6	—
				induction			
17	19 610	213	all	0–600 V	0.0109	114.0	18.3
17	4229	171	all	601–15 000 V	0.0404	76.0	91.5
				synchronous			
2	13 790	10	all	0–600 V	0.0007	35.3	35.3
11	4276	136	all	601–15 000	0.0318	175.0	153.0
6	558	31	all	direct current	0.0556	37.5	16.2
				induction			
9	16 105	196	petrochemical	0–600 V	0.0122	123.4	—
10	3834	156	petrochemical	601–15 000 V	0.0407	74.3	—
				synchronous			
1	13 750	10	petrochemical	0–600 V	0.0007	35.3	35.3
6	4027	130	petrochemical	601–15 000 V	0.0323	175.8	—

Response was adequate in this survey to show an intermediate voltage class (1001–5000 V) not shown in the previous survey. Induction motors in the first two voltage classes show failures rates very nearly the same, with the lower voltage class slightly higher. Both are substantially higher than the earlier results (Table II).

The response for synchronous motors was dominated by the 1001–5000-V class, and again the new survey shows a failure rate twice that of the higher voltage rated synchronous motors in Table II. The new results show failure rates for synchronous and induction motors approximately equal for the same voltage class. The "petrochemical" industry shows a slightly higher failure rate for synchronous motors than for all industries.

The new survey obtained data on wound rotor induction motors with results showing a failure rate only slightly less than induction motors of the same lower voltage class. The next higher voltage class has a failure rate less than half that of synchronous and induction motors.

Although the sample size for dc motors was considered inadequate, this failure rate was the only one showing some consistency with the previous survey. The previous survey did not show a voltage class for dc motors.

Overall, the median hours downtime per failure was reported as less in the new survey than in the 1973 survey. Again the downtime reported was biased with unusually high periods and the average value for each class is consistently higher than the median value. The overall average and median downtime values calculated for all categories in this table include the downtime data omitted in the specific categories with "small sample size." Also, downtime for two failures was exceptionally and unusually high and therefore omitted from the results. One was reported as 960 h for an induction motor in the 0–1000-V class and replaced with a spare to restore service. The other was reported as 6570 h for an induction motor in the 1001–5000-V class and repaired during normal working hours.

Horsepower

Table III is presented to show a relationship of failure rate with size. The response gives a good comparison between the first two size categories with the failure rates calculating very nearly the same and also approximating those in Table I showing voltage classes. The third size category (5001–10 000 hp) shows a relatively high failure rate but calculated with a small population in sample size.

Speed

Failure rate is generally considered affected by speed, but Table IV shows somewhat unexpected results. The highest speed range, essentially 3600 r/min was included in this survey because of the increasing popularity in industry of two-pole motors. These results show the highest speed motors as most reliable and the lowest speed as least reliable.

Enclosure Type

This population type was added to expand on any notable effects on failure rate. Table V shows that open motors experienced the highest failure rate among those with substantial sample size. Depending on the application this result might have been expected except the table below on causes does not support this result in the obvious causes of moisture and aggressive chemicals. It is suspected that more supporting data may be hidden in the relatively high response to causes reported as "other."

TABLE III
HORSEPOWER VERSUS FAILURE RATE

	201-500 hp	501-5000 hp	5001-10 000 hp	> 10 000 hp	Not Specified
Sample size (unit-yr)	3185.6	1822.5	46.1	17.2	13.5
Number of failures	217	133	10	—	—
Failure rate (failures/unit-yr)	0.0681	0.0730	0.2169	—	—

TABLE IV
SPEED VERSUS FAILURE RATE

	0–720 r/min	721–1800 r/min	1801–3600 r/min	Not Specified
Sample size (unit yr)	657.1	3219.8	1194.6	13.5
Number of failures	66	232	62	—
Failure rate (failures/unit yr)	0.1004	0.0721	0.0519	—

Environment

In Table VI the survey results show failure rate as affected by indoor and outdoor applications. It was expected that outdoor motors would show a higher failure rate than indoor motors, but the opposite was true. This follows from Table V which shows open type enclosures with the highest failure rate. One might conclude that when all environmentally related causes are combined as one, they support the results of Tables V and VI.

Duty Application

This population type breaks out continuous and intermittent application in Table VII. The total sample size was heavily dominated by continuous duty use with this category showing the highest failure rate at about twice that of intermittent duty. Some motors were reported as intermittent in a backup or standby role and operated only a small fraction of the period reported which may account partly for the large difference in failure rates.

Service Factor

Reliability versus service factor (SF) is an important consideration for those who must apply motors at varying load conditions that sometime exceed the normal nameplate rating of the motors. Table VIII shows a higher failure for 1.15-SF

TABLE V
ENCLOSURE TYPE VERSUS FAILURE RATE

	Open	Weather Protected	Totally Enclosed (TEFC, E.P., D.I.P)	Totally Enclosed (Open Pipe Vent)	Totally Enclosed (Water-Air)	Totally Enclosed (Air-Air)	Not Specified
Sample size (unit yr)	2597.6	569.5	1339.9	40.7	119.5	332.5	85.2
Number of failures	224	25	78	6*	6*	20	1*
Failure rate (failures/unit yr)	0.0862	0.0439	0.0582	*	*	0.0602	*

*Small sample size.

TABLE VI
ENVIRONMENT VERSUS FAILURE RATE

	Indoor	Outdoor	Not Specified
Sample size (unit yr)	3359.9	1663.8	61.3
Number of failures	263	97	—
Failure rate (failures/unit yr)	0.0783	0.0583	—

TABLE VII
DUTY APPLICATION VERSUS FAILURE RATE

	Continuous	Intermittent	Not Specified
Sample size (unit yr)	4412.2	659.3	13.5
Number of failures	334	26	—
Failure rate (failures/unit yr)	0.0757	0.0394	—

TABLE VIII
SERVICE FACTOR VERSUS FAILURE RATE

	1.0SF	1.15SF	>1.15SF	Not Specified
Sample size (unit yr)	2557.9	2314.9	102.3	109.9
Number of failures	158	187	4*	11
Failure rate (failures/unit yr)	0.0618	0.0808	0.0391	0.1001

*Small sample size.

TABLE IX
AVERAGE NUMBER OF STARTS/DAY VERSUS FAILURE RATE

	<1	1-10	11-30	>30	Not Specified
Sample size (unit yr)	3654.8	1274.5	104.9	37.3	13.5
Number of failures	257	97	2*	4*	—
Failure rate (failure/unit yr)	0.0703	0.0761	0.0191	0.1072	—

*Small sample size.

TABLE X
POWER SUPPLY GROUNDING TYPE VERSUS FAILURE RATE

	Solid Ground	Impedence Ground	Ungrounded	Not Specified
Sample size (unit yr)	2287.7	1873.9	909.9	13.5
Number of failures	127	150	83	—
Failure rate (failures/unit yr)	0.0555	0.0800	0.0912	—

motors than for 1.0-SF motors. Under causes, overheating was reported as a significant failure initiator which raises the suspicion that exceeding temperature rises might be an application problem. These results do not show the effect of full service factor operation on field equipment of synchronous and dc motors or on secondary equipment of wound rotor motors. However, slip rings and brushes were not reported as obvious major problem areas as shown in Table XI.

Average Number of Starts per Day

This population type was expected to provide data to show the effects of increasing severity in duty cycle, as related to starting, on failure rate. Surprisingly, the results (Table IX) show only a slight difference in failure rate between the first two categories. The response was disappointing in the last two categories, and no obvious trend in evident.

Power Supply Grounding Type

Much has been written about the effects of how the power supply system neutral is handled on reliability of electrical equipment and especially on motors. Table X shows results that support many generalizations and expected consequences of grounding types. The least failure rate is with solidly grounded power supplies, and the highest is with ungrounded power supplies. Commonly expected causes of failures in ungrounded systems include transient overvoltage and abnormal voltage levels, but the table on causes did not support this.

TABLE XI
FAILED COMPONENT

Failed Component*	Induction Motors	Synchronous Motors	Wound Rotor Motors	DC Motors	Total All Types
	Number of Failures				
Bearing	152	2	10	2	166
Windings	75	16	6	—	97
Rotor	8	1	4	—	13
Shaft or CPLG	19	—	—	—	19
Brushes or slip ring	—	6	8	2	16
External device	10	7	1	—	18
Not specified	40	9	—	2	51

* Some respondents reported more than one failed component per motor failure.

However, insulation breakdown and deterioration from age might be interpreted as being affected by ungrounded systems.

Failed Component

Table XI shows which components failed most often for the four types of motors surveyed. Similar to the previous survey, bearings and windings were the predominate trouble areas. However, in this survey bearings by far led all other individual components in failures. In the previous survey windings failed most often. A significant number of failures occurred where the failed component was not specified in this survey.

Time Failure Discovered

The data in Table XII give an indication of when users discover most failures. Two-thirds of the failures were discovered during normal operation, and almost one third were discovered during testing or maintenance. Many feel that under a good maintenance program, most failures are discovered or prevented during testing or maintenance. Table XIV shows that about one-third of the total population reported excellent maintenance. The previous survey showed the same trend in when failures were discovered. The causes table lists major types that support the result of most failures being discovered during normal operation.

Causes of Failures

These results, shown in Table XIII are very close to those of the 1973 survey with some minor differences. The three most common failure initiators are mechanical breakage, overheating, and insulation breakdown. These causes, combined, are supportive of the previous survey results.

The major contributing cause reported is normal deterioration from age, as was also a major contributer in the other survey. Unlike the previous survey, high vibration and poor lubrication were also reported as significant causes which reinforce the problem areas of mechanical breakage and consequently bearing failures. Both surveys reported defective components and inadequate maintenance as major underlying causes.

Considering the combined contributing causes related to environmental conditions such as high ambient temperature, abnormal moisture, aggressive chemicals, and poor ventilation, the failure rates of open and indoor motors shown in

TABLE XII
TIME FAILURE DISCOVERED

	Number of Failures	Percent of Total
During normal operation	240	66.7
During routine maintenance or testing	101	28
Other	13	3.6
Not specified	6	1.7

TABLE XIII
CAUSES OF FAILURES

	Number of Failures	Percent
Failure Initiator		
1) Transient overvoltage	5	1.5
2) Overheating	45	13.2
3) Other insulation breakdown	42	12.3
4) Mechanical breakage	113	33.1
5) Electrical fault or malfunction	26	7.6
6) Stalled motor	3	0.9
7) Other	107	31.4
Failure Contributor		
1) Persistent overloading	14	4.2
2) High ambient temperature	10	3.0
3) Abnormal moisture	19	5.8
4) Abnormal voltage	5	1.5
5) Abnormal frequency	2	0.6
6) High vibration	51	15.5
7) Agressive chemicals	14	4.2
8) Poor lubrication	50	15.2
9) Poor ventilation or cooling	13	3.9
10) Normal deterioration from age	87	26.4
11) Other	65	19.7
Failure Underlying Cause		
1) Defective component	62	20.1
2) Poor installation/testing	40	12.9
3) Inadequate maintenance	66	21.4
4) Improper operation	11	3.6
5) Improper handling/shipping	2	0.6
6) Inadequate physical protection	19	6.1
7) Inadequate electrical protection	18	5.8
8) Personnel error	21	6.8
9) Outside agency other than personnel	12	3.9
10) Motor-driven equipment mismatch	15	4.9
11) Other	43	13.9

TABLE XIV
MAINTENANCE VERSUS FAILURE RATE

Maintenance Quality and Cycle	Sample Size (Unit Yr)	Number of Failures	Failure Rate (Failures/Unit Yr)	Median Hours Downtime/Failure	Average Hours Downtime/Failure
Excellent					
<12 mo	834.0	93	0.1115	8	53.6
12–24 mo	660.1	24	0.0364	24	40
>24 mo	285.5	9	0.0315	36	48
All	1779.6	126	0.0708	16	50.9
Fair[a]					
<12 mo	1776.8	155	0.0872	16	37.7
12–24 mo	967.7	39	0.0403	54	166.3
>24 mo	167.0	12	0.0719	165	264.4
Not Specified	4.0	1*	*	*	*
All	2915.5	207	0.0710	16	87.3
Poor[b]					
<12 mo	37.1	3*	*	*	*
12–24 mo	195.4	15	0.0563	96	83.6
>24 mo	6.0	1*	*	*	*
All	238.5	19	0.0797	72	70.7
None	123.3	7*	*	*	*
Not specified	28.0	1*	*	*	*

*Small sample size.
[a] 960 h downtime for one failure omitted.
[b] 6570 h downtime for one failure omitted.

Tables V and VI may not be abnormal. Additionally, this survey shows improper application as a significant problem area when the combined effects of poor installation/testing, physical and electrical protection, personnel error, and equipment mismatch are considered.

Maintenance Versus Failure Rate

Table XIV shows the results of failure rate compared to maintenance quality and maintenance cycle as reported in this survey. The previous survey results did not report maintenance cycle versus failure rate. However, Table XV has arranged available data to show quality versus failure rate. One notable difference can be seen in the maintenance cycle response in each quality category. The previous survey showed a trend in more frequent maintenance associated with higher quality. In the new survey response was greatest in the most frequent maintenance cycle in both the excellent and fair quality categories. So an obvious trend is not evident.

In both surveys, the largest response was to fair maintenance. However, the new survey had much more response to poor maintenance. Both had about the same division in response between fair and excellence qualities.

The most surprising result in the new data is the failure rate under reported excellent maintenance. Excellent maintenance with the most frequent cycle had the highest failure rate. Overall, in each quality category there is very little difference in failure rate.

The downtime listed in Table XIV does show an expected trend between the categories. The data suggest that the higher the quality and more frequent the cycle, the less severe the failure.

Description of Maintenance

Response was adequate to present a description of the methods of maintenance reported under the categories of quality and cycle. In Table XVI data are listed as percentages of the number of types of motor population reported (e.g., one plant reported six different types of motors with maintenance data listed for each type; these were counted as six population types for the purposes of this table). The differences and similarities between the various categories are quite obvious. The most commonly used method of maintenance under excellent and fair is "clean."

TABLE XV
1973 MAINTENANCE QUALITY VERSUS FAILURE RATE

Maintenance Quality and Cycle	Sample Size (Unit Yr)	Number of Failures	Failure Rate (Failures/Unit Yr)
Excellent			
<12 mo	14 650		
12–24 mo	1372		
>24 mo	1259		
All	17 281	77	0.0045
Fair			
<12 mo	121		
12–24 mo	21 930		
>24 mo	2958		
All	25 009	439	0.0175
Poor			
<12 mo	—		
12–24 mo	—		
>24 mo	74		
All	74	2*	0.0270*

*Small sample size.

Failure Repair/Replace Urgency

Table XVII is intended to give some insight to the urgency reported for restoring motors to service and the resulting downtime of the failures. In these data the following two responses were considered unusual and exceptional and were omitted: downtime for one failure under "repair during normal working hours" was reported as 6570 h and downtime

TABLE XVI
DESCRIPTION OF MAINTENANCE REPORTED

Maintenance Description	Excellent < 12 mo	Excellent 12–24 mo	Excellent > 24 mo	Excellent All	Fair < 12 mo	Fair 12–24 mo	Fair > 24 mo	Fair All	Poor < 12 mo	Poor 12–24 mo	Poor > 24 mo	Poor All
	Percent of Population Types											
1) Visual	12.5	2.3	—	6.5	24.7	43.1	41.7	32.6	—	31.2	—	33.3
2) Meggar	39.6	47.7	25.0	40.7	53.5	50.8	33.3	51.1	—	12.5	—	23.8
3) Clean	43.7	56.8	25.0	46.3	91.1	38.5	83.3	71.4	—	37.5	—	33.3
4) Lub. and/or filters	33.3	36.4	37.5	35.2	64.4	52.3	16.7	56.8	—	62.5	—	52.4
5) Vibration check	20.8	2.3	—	10.2	29.7	—	16.7	18.0	—	—	—	—
6) Bearing check	18.7	34.1	43.7	28.7	1.0	16.9	41.7	9.5	—	6.2	—	4.8
7) Reinsulate	4.2	—	18.7	4.6	—	3.1	33.3	3.4	—	6.2	—	4.8
8) Ampere or temperature check	4.2	—	—	1.9	3.0	13.8	8.3	7.3	—	12.5	—	9.5
9) Air gap check	2.1	20.5	—	9.3	8.9	—	—	5.1	—	—	—	—
10) Alignment	4.2	15.9	—	8.3	—	—	—	—	—	—	—	—
11) Change or check brushes	6.2	4.5	—	4.6	8.9	1.5	8.3	6.2	—	—	—	—
12) Overhaul	—	—	—	—	—	—	8.3	—	—	—	—	—
13) Paint	—	—	—	—	5.9	—	33.3	5.6	—	—	—	—
14) Check cooling system	—	—	—	—	3.0	—	—	1.7	—	—	—	—
15) Not specified	22.9	22.7	37.5	25.0	—	3.1	—	1.1	—	—	—	4.8
Number of Population Types	48	44	16	108	101	65	12	178	4	16	1	21

TABLE XVII
REPAIR/REPLACE URGENCY VERSUS DOWNTIME

	Number of Failures	Average Hours Downtime/Failure	Median Hours Downtime/Failure
Normal working hours[a]	87	97.7	24.0
Round the clock	45	81.4	72.0
Replace with spare[b]	111	18.2	8.0
Low priority	4*	370.0*	400.0*
Not specified	6*	288.0*	240.0*
Total	251	69.3	16.0

*Small sample size.
[a] 6570 h for one failure omitted.
[b] 960 h for one failure omitted.

TABLE XVIII
1973 REPAIR/REPLACE URGENCY VERSUS DOWNTIME

	Number of Failures	Average Hours Downtime/Failure
Normal working hours	323	136.0
Working round the clock	54	110.3
Replace with spare	94	21.0
Low priority	7*	*
Total	478	108.5

*Small sample size.

for one failure under "replace with spare" was reported as 960 h. Data from the previous survey were rearranged and presented here as Table XVIII. Unlike the previous survey, median hours downtime per failure is included in the new data to reflect the influence of numerous long downtime periods reported.

In the first two categories the new survey shows obvious shorter average downtime per failure than the older survey, but the category on replace-with-spare is very close. An obvious uncertainty in the new results is evident in the median value for round-the-clock urgency. The downtime is higher than for less urgent repair. This suggests the possibility of some data being reported erroneously. Another interesting result is that half of the failures were reported as "replaced with spare" in the new survey. Only about one fifth of those of the old survey were in this category. This might be expected since the new survey covered only larger more critical applications. The previous survey results presented no downtime data for the "low priority" category, and thus the total average in Table XVIII is calculated using only the data shown.

GENERAL DISCUSSION

It is the general consensus of the subcommittee sponsoring this activity that the new motor reliability data of this survey, contingent on reporting accuracy of the respondents, is more practical and useful for its intended purpose than the older survey data because of the restrictions on age and size. This survey also produced an attractive cross section of experience in the number of plants represented. One very obvious difference in the findings in this survey over the 1973 survey is the general trend of higher failure rates in the new data.

For obvious reasons, maintenance is expected to have a significant impact on failure rate and downtime. This paper, for the most part, presents results of responses to the population types as requested in the survey questionnaire.

TABLE XIX
90 PERCENT CONFIDENCE INTERVALS FOR FAILURE RATE

	Induction Motors	Synchronous Motors	Wound Rotor Motors	DC Motors	All
Lower limit	0.0659	0.0583	0.0350	0.0169	0.0644
Survey result	0.0732	0.0777	0.0515	0.0393	0.0708
Upper limit	0.0798	0.1026	0.0737	0.0699	0.0772
Percent deviation, L	10	25	32	57	9
Percent deviation, U	9	32	43	78	9

There are many possible combinations of categories, especially including those related to maintenance, that can be formulated from the responses. The questions and uncertainties stimulated by the results presented here warrant continued analysis and an additional report is planned to present this expanded analysis of the correlation between the various categorical results with particular emphasis on the effects of maintenance.

As an additional tool, Table XIX provides a measure of confidence in the use of the new data in this report. The table illustrates the statistical limits within which 90 percent of the failures could be expected to occur. The confidence limits are based on curves assuming a homogeneous population since it would be impractical to search out every variable affecting confidence levels and determine curves for each one.

APPENDIX

REASONS FOR CONDUCTING A NEW RELIABILITY SURVEY ON MOTORS

By: Power Systems Reliability Subcommittee,
Industrial and Commercial Power Systems Committee,
IEEE Industry Applications Society
September 1981

Charles R. Heising (*Chairman*)	Don W. McWilliams
James W. Aquilino	William T. Miles
Carl E. Becker	Joseph J. Moder
Richard N. Bell	John H. Moore
Thomas V. Booth	Pat O'Donnell
Williard H. Dickinson	A. D. Patton
Bruce Douglas	Chinan Singh
Phillip E. Gannon	Wayne L. Stebbins
Raymond E. Gibley	Howard P. Stickley
Ian Harley	Harold T. Wane
Thomas Key	Stanley J. Wells

The IEEE "Report on Reliability Survey of Industrial Plants, Part I: Reliability of Electrical Equipment" published in 1973 contained information on failure rates and downtime/failure for motors.

In their meeting on May 12, 1980, in Houston, TX, and in keeping with their commitment to update the previous survey, the Power Systems Reliability Subcommittee of the IEEE Industrial Power Systems Department is conducting a new survey on the reliability of motors.

Overall the main purpose of this reliability survey is to identify failure data and the effects of preventive maintenance on important classes, types, and applications of motors, thus providing the designer and planner the valuable basic information needed to install a reliable and economic system.

The data in the previous reliability survey show that for motors rated 0–600 V the failure rate for induction motors is 15 times higher than synchronous motors. Since induction motors are normally considered more reliable than synchronous motors, it is presumed that the survey data were inadequate to cover enough applications to bring this out.

The data in the previous reliability survey shows that for induction motors 0–600 V (this category represents over 50 percent of the total motor population), the failure rate is 0.0109 (one unit failure per 92 unit years). This failure rate appears to be unreasonably low when compared with other equipment categories (i.e., motor starters = one failure per 72 unit years, steam turbine driven generators one failure per 32 unit years, transformers one failure per 244 unit years). Failure rate of this overall class of motors is obviously valuable information to users and manufacturers. This new survey will support or update this failure rate.

Motor designs, shop fabrication facilities, and manufacturing procedures for NEMA frame ac motors (ratings 1–200 hp) are significantly different from those for motors rated over 200 hp. In the previous motor reliability survey, the failure data for motors of all horsepower ratings were lumped together. The new motor reliability survey will collect failure data only on ac motors rated above 200 hp. Usually, motors rated above 200 hp are driving critical equipment. The reliability of these large motors is of prime importance to the industrial system design engineer. Recent user experience with reliability of the current generation of large ac motor designs (over 200 hp) indicates a trend toward a higher number of failures per unit time.

The previous survey data show that the industry average time to repair ac low-voltage motors (0–600 V) is 114 h compared to 76 h for medium-voltage ac motors (601–15 000 V). This information should be updated with a larger sample size of medium voltage motors.

The increased emphasis on minimizing capital investment in industrial facilities has resulted in a significant increase in the use of two-pole ac induction motors. Because of these relatively high speeds (3600 r/min), reliability of these two-pole motors is expected to be lower than the lower speed ac motors (four and six poles). The previous reliability study did not differentiate between 3600 r/min two-pole motors and the slower speed motors. The new motor reliability survey will collect separate reliability data on two-pole motors. Relative reliability data on two-pole motors and those with four or more poles will be useful to the industrial design engineer in evaluating the equipment cost savings inherent in two-pole (3600 r/min) operating speeds for motor and associated driven equipment.

The database for the previous reliability study (both unit years and number of units) represents something in the order of only a few hundredths of a percent of the total motor population.

The mailing list for the new survey will be expanded and edited to obtain failure data on a larger percentage of the total motor population.

COMPANY NAME AND PLANT: ______________________

INDUSTRY TYPE: ______________________

PERIOD REPORTED - FROM: MONTH ________ YEAR ______

TO: MONTH ________ YEAR ______

LOCATION: ______________________

CONTAMINATION LEVEL AND TYPE: ______________________

Fig. 1. Reliability survey for electric motors larger than 200 hp.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
	Identification Number	Total Number of Motors	Type	Horsepower	Voltage	Speed	Enclosure Type	Environment	Duty Application	Service Factor	Average Number of Starts/Day	Grounding Type (Power Supply)	Maintenance Cycle	Maintenance Quality	Brief Description of Maintenance
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															

Fig. 2. Total population data.

COVER LETTER

Pat O'Donnell
El Paso Natural Gas Company
P.O. Box 1492
El Paso, TX 79978
(915) 541-2080

Dear Sir,

RE: Motor Reliability Survey for Motors Larger than 200 hp

The Reliability Subcommittee of the Industrial Power Systems Department requests your cooperation in a survey to determine the reliability of electric motors in industrial installations. As with previous surveys you may have seen, this survey is a followup to the general reliability survey of plant equipment in 1971 and is intended to provide more meaningful data on motors. Attached for your information is a report by the subcommittee on reasons for the survey.

The results of this survey will be published in an IEEE paper for value to system planners and designers in reliability evaluation of alternatives. Of course, individual responses will be held in strict confidence and only summaries published.

Survey Instructions

The survey form is reasonably self-explanatory, but a sample filled-out form is included for your guidance and some brief instructions follow. We emphasize that all requested data are important, but where some of these data are unknown, simply provide the known data and leave the other spaces blank. We also encourage any explanatory comments as you feel appropriate. If additional data sheets are needed, please duplicate those provided. *This survey is restricted to motors greater than 200 hp and no older than 15 years.*

General Data [Fig. 1]:

1) It is vitally important that the period reported be given.

2) Plant contamination level and type should be your best estimate.

Total Population Data [Fig. 2]:

1) Using the "total population" data block, give requested data for all motors greater than 200 hp and 15 years old or less, in service during the period reported *whether or not failures have occurred.* (Note: When the period reported exceeds the age of a motor, use separate data sheets for the new motors.)

2) Use the categories attached to the data block to describe the data.

3) When one data sheet is insufficient to list the total population of motors, use consecutive identification numbers in the first column of the data sheets (e.g., 1, 2, 3, etc., for first sheet; 11, 12, 13, etc., for the second sheet, and so on).

Failure Data [Fig. 3]:

1) List each motor failure event separately using the attached categories to describe the failure.

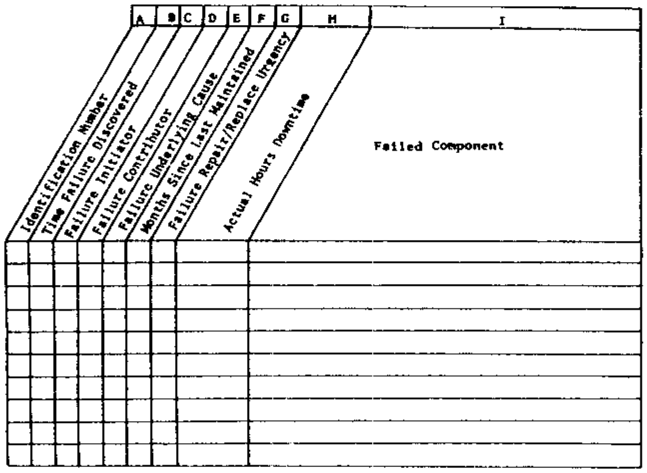


Fig. 3. Failure data.

2) Identify each failure with the corresponding identification number in the "total population" data.

3) Under column I describe the component on the motor that failed.

Our schedule dictates that responses be received no later than April 15, 1982. Your participation in this project will be greatly appreciated.

Sincerely,

Pat O'Donnell
Chairman, Motor Reliability Survey Working Group

REFERENCES

[1] IEEE Committee Report, "Report on reliability survey of industrial plants," *IEEE Trans. Ind. Appl.*, Mar./Apr., July/Aug., and Sept./Oct. 1974.

[2] *IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems*, IEEE Standard 493, pts. I, III, IV, and VI.

Discussion

P. F. Albrecht (General Electric Company, Schenectady, NY), **E. L. Owen** (General Electric Company, Schenectady, NY), and **D. K. Sharma** (Electric Power Research Institute, Palo Alto, CA): This Working Group Report provides interesting and timely information which adds to a growing body of information about the reliability of electric motor drives. This information should be useful to owners, operators, and designers of motor equipments in their efforts to obtain improved motor reliability. The discussers welcome this additional information and support the objectives of the Working Group. We are hopeful that information of this type will become increasingly available as we feel it will assist all those involved in motor applications in obtaining increased reliability.

Surveys have been conducted by other groups seeking similar data for their industries. Under the sponsorship of the Electric Power Research Institute (EPRI), Palo Alto, CA, General Electric conducted an Industry Assessment Study (IAS) to evaluate the present reliability of powerhouse motors and to identify design and operational characteristics which, through advanced development, offer the potential of increased motor reliability [3]. Further work is presently underway to add data received after the closing date originally scheduled for the EPRI study. Analysis based on this additional data will be published at a later date.

We have compared the scope and results of this survey, as presented by the Working Group, with the results reported for the EPRI survey. Although the motor populations in the two studies are from different industries, we find many aspects of this Working Group Report which corroborates the findings of the EPRI study. The survey response achieved in the two studies are compared in Table XX.

In the EPRI study, it was found that failures subsequent to the first failure had a much different distribution than time to first failure. Therefore, the primary analysis was conducted in terms of time to first failure. Thus the failure rate from the EPRI study is not directly comparable with the Working Group results.

An important result of the EPRI study was to identify those motor components which are most subject to failure. This information was considered in setting priorities for development work to improve motor reliability. The type of motor involved in the EPRI survey was largely the squirrel-cage induction motor (approximately 97 percent of the "known" types were reported as cage induction motors), and the information about failure by component is most representative of this motor type. There are differences in the categories of

TABLE XX
SCOPE OF RELIABILITY STUDIES

Parameter Working Group — Nomenclature — (EPRI)		Working Group	EPRI Phase I
Number of companies	(Utilities)	33	56
Number of plants	(Units)	75	132
Number of motors	(Motors)	1141	4797
Total population (unit-years)	(Motor-years)	5085	24914*
Total failures		360	872
Failure rate (all motors)		0.0708	0.035*

*Based on first failure only.

failed component as reported in the two studies, which makes a direct comparison of results very difficult.

However, both studies found that for squirrel-cage induction motors, bearing and stator winding related failures accounted for approximately three-fourths of all failures, while roto. related failures accounted for only ten percent of the failure.. These results seem to corroborate each other and gives us greater confidence in our conclusions as to where emphasis should be placed. Fig. 4 and Table XXI show the percentage failure by component as reported by the EPRI study.

As a part of the EPRI study, additional analysis was performed to understand reliability issues better. We found that the most significant variable affecting motor failure rate was the plant (unit) where the motor was installed. For example, in the EPRI study a 90 percent confidence interval for failure rate of each of the 132 units was calculated. If all units had the same underlying failure rate, about 13 units would have a 90 percent confidence interval which does not include the failure rate for the entire population. However, in the EPRI study, 40 units had a 90-percent interval entirely below the population average, and 22 units were entirely above the population average.

We felt it was important to consider this unit variation when investigating other factors such as application or size effects. Was any such effect between respondents investigated in the Working Group survey? In particular, could the effect of horsepower noted in Table III of your report be *partly* due to the different companies represented in various size ranges.

Table III of the Working Group report suggests a tendency for the motor failure rate to increase with motor size. Booz, *et al.* also made an analysis based on motor size [4]. However, it was felt that horsepower per pole, rather than horsepower, better represented exposure to such failure mechanisms as

- fatigue resulting from differential expansion,
- high stress during operation,
- susceptibility to lateral vibration.

Would it be possible to analyze the Working Group data on the basis of horsepower per pole, similar to the EPRI analysis?

As a final comment, the detail of analysis must be commensurate with the size of the database. With the large database in the EPRI Phase II study, we hope to be able to investigate such factors as the effect of first failure on subsequent failure rate. We again compliment the Working Group on a good survey and hope to see more of the same.

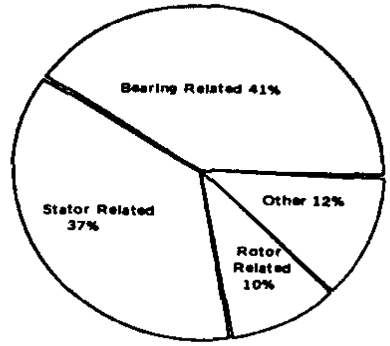


Fig. 4. Percentage failure by component.

TABLE XXI
PERCENTAGE FAILURE BY COMPONENT

Bearing related	
Sleeve bearings	16
Antifriction bearings	8
Seals	6
Thrust bearing	5
Oil leakage	3
Other	3
Total	41
Stator related	
Ground insulation	23
Turn insulation	4
Bracing	3
Wedges	1
Frame	1
Core	1
Other	4
Total	37
Rotor related	
Cage	5
Shaft	2
Core	1
Other	2
Total	10

REFERENCES

[3] "Improved motors for utility applications," EPRI EL-2678, vol. 1, 1763-1, final rep., Oct. 1982.
[4] "Improved motors for utility applications, industry assessment study," EPRI EL-2678, vol. 2, 1763-1, final rep., Oct. 1982.

Pat O'Donnell (Coordinating Author): First, to address specific questions of the Discussion, we find the result of variation of reliability of motors in three different categories of units or groups very interesting and useful. However, the IEEE survey data do not lend themselves to this specific analysis. Our immediate response to this result is concern over the obvious cause or reason for this grouping to emerge. The IEEE data results attempted to classify industry types, which

may follow a similar purpose, but the results related to maintenance more specifically categorize users in the IEEE report. We believe the IEEE and EPRI surveys are distinctly different in this respect but, as such, are complementary.

The IEEE survey collected data on a range of horsepower sizes and a range of speed ratings. We are not able to identify a fine resolution of horsepower per pole ratios but only general ranges. A quick analysis of our data for induction motors only allows the result shown in Table XXII.

The IEEE survey emphasized motor size and speed range separately with the intent of comparing these categories mutually and with others. Again, these results seem to be an excellent complement to the EPRI results, which diminish the significance of motor size in horsepower and speed as separate considerations. That is, a small high-speed motor might have the same horsepower/pole ratio as a large slow-speed motor.

We also are enthused about the added confidence in our data showing similarities in failed component trends. Bearing and winding failure trends were very similar in the two survey results. The IEEE survey did not collect detailed data to break down failed components into more subcategories of types, but data were collected on causes which helped determine *why* bearing and winding failures occurred. We are very interested in whether or not the difference in reliability between the "high" and "low" groups in the EPRI results supports the causes found in our survey results.

Finally, there is a significant difference in the basis of the two surveys that add, possibly, to some of the differences in results. The IEEE survey acquired data only on motors larger than 200 hp. The EPRI survey included sizes down to and including 100 hp. This surely accounts for some of the difference in total populations, but additionally, the IEEE data exclude standard NEMA frame size motors. It would be of interest to compare our results with EPRI results excluding motors 200 hp and smaller. This working group is enthused about the EPRI results, and we look forward to seeing further analysis of the data.

TABLE XXII
HORSEPOWER VERSUS SPEED
(INDUCTION MOTORS)

	Number of Failures	Unit Years	Failure Rate
0–720 r/min			
201–500 hp	7	137.92	0.0508
501–5000 hp	12	175.16	0.0685
5001–10 000 hp	—	—	—
> 10 000 hp	—	—	—
721–1800 r/min			
201–500 hp	148	1922.43	0.0770
501–5000 hp	66	740.1	0.0892
5001–10 000 hp	1	2.83	0.3534
> 10 000 hp	—	7.5	—
3600 r/min			
201–500 hp	42	655.75	0.0640
501–5000 hp	16	358.66	0.0446
5001–10 000 hp	—	—	—
> 10 000 hp	—	—	—

Pat O'Donnell (S'64–M'68–SM'80) was born in El Paso, TX, in 1942. He received the B.S.E.E. degree from Texas Western College (now University of Texas at El Paso) in 1965.

After brief employment with Schlumberger Well Surveying Corporation, he joined El Paso Natural Gas Company in 1966 and is presently Principal Electrical Engineer in the main office Engineering Department in El Paso.

Mr. O'Donnell is currently active in the Industrial and Commercial Power Systems Department of the IEEE Industry Applications Society and currently serves as Secretary of the department. He is a member of and past Chairman of the Power System Technologies Committee and current Chairman of the Emergency and Standby Power Systems Subcommittee. He is also a member of the Power Systems Reliability Subcommittee, serving as Chairman of the Motor Reliability Working Group, and the Power Systems Analysis Subcommittee. Outside of IEEE, he is a member of the ASME Standards Committee on Ignition Systems for Industrial Engines. He is a Registered Professional Engineer in the States of Texas and New Mexico.

Report of Large Motor Reliability Survey of Industrial and Commercial Installations, Part II

MOTOR RELIABILITY WORKING GROUP
POWER SYSTEMS RELIABILITY SUBCOMMITTEE
POWER SYSTEMS ENGINEERING COMMITTEE
INDUSTRIAL AND COMMERCIAL POWER SYSTEMS DEPARTMENT
IEEE INDUSTRY APPLICATIONS SOCIETY

***Abstract*—In 1983 the initial results of an IEEE survey on large motors was published and presented at the 1983 I&CPS Conference. This was the first presentation of the results of a survey completed in 1982 of motors larger than 200 hp and no older than 15 years. The results presented here of the 1982 survey are to investigate the data further to address questions generated by the results of the earlier paper, to find additional correlations of the reliability criteria of some of the more interesting categories, and to bring out more results and categories available from the survey data. For information on the overall survey response and the general results of the surveyed categories, refer to the previous paper.**

INTRODUCTION

THE SECOND set of results of the 1982 survey of the reliability of large motors in industrial and commercial installations is summarized in Tables I-XIII. Reference is occasionally made to the results presented in 1983 which will hereafter be called Part 1 [1].

In addition to new comparisons of categories to reveal more detailed analysis of the results of Part 1, these new results focus more on the effects of maintenance and especially more on the effects of causes. Of particular interest are the comparisons of reliability data for induction and synchronous motors, further analysis of service factor and speed, further analysis of bearing and winding failures, a closer look at the effect of inadequate maintenance on reliability, additional comparisons of indoor and outdoor applications, and additional grounding type comparisons.

Some comments about the data in the tables are in order to clarify some questions that may arise. Where no data are given, there was either no response or the number of failures (FLR's) and population were insufficient for meaningful results. A footnote marks insufficient response where failures were reported, but the total was less than eight. This is in keeping with the standard of credibility previously established by the Power Systems Reliability Subcommittee. In preparation of this paper, a careful, closer look was taken and some of the minor errors in counting were corrected. Thus the total count in some areas will differ slightly from those of Part 1. However, the corrections are minor and no trends are affected. Also, as in the Part 1 results, downtime (DT) for two failures was omitted. One was 960 h for an induction motor, 0-1000 V and replaced-with-spare. The other was 6570 h for an induction motor, 1001-5000 V.

As with other survey results by this subcommittee, a brief discussion is included for each table emphasizing significant results, but there is no intent to draw definite conclusions. The tables are presented representing results from the data reported in the survey.

Paper IPSD 84-36, approved by the Power Systems Technologies Committee of the IEEE Industry Applications Society for presentation at the 1984 Industrial and Commercial Power Systems Conference, Atlanta, GA, May 7-10, 1984. Manuscript released for publication November 5, 1984.

Members of IEEE Motor Reliability Working Group
R. N. Bell is with E.I. du Pont de Nemours & Company, Engineering Department, Louviers Building, L5231, Wilmington, DE. 19898.
C. R. Heising is with Industrial Reliability Tech, 216 Farwood Road, Philadelphia, PA, 19151.
P. O'Donnell, *Coordinating Author*, is with El Paso Natural Gas Company, Tex & Stanton Box 1492, El Paso, TX 79978.
C. Singh is with Texas A&M University, Department of Electrical Engineering, College Station, TX 77843.
S. J. Wells is with Union Carbide Corporation, P.O. Box 50, Hahnville, LA 70057.

INDUCTION AND SYNCHRONOUS MOTORS

The results in Part 1 of the survey showed induction and synchronous motors with nearly equal failure rates. Some believe that synchronous motors, because of their complexity, should fail more than induction motors. Table I compares these types to various categories to identify any notable differences.

Two categories showed some deviation from the general results of Part 1. Where response was adequate in the first two classes, starts per day clearly affected synchronous motors more than induction motors. The induction motor failure rate changed very little, but the synchronous motor failure rate increased with an increase in starts per day. In the speed category it was the induction motors that showed some deviation from the trend of Part 1. One observation is the increase in failure rate with speed for the first two classes of speed. A second observation is the high failure rate for synchronous motors in the slowest speed class. So the two types of motors had opposite trends in failure rate with speed. The influence of synchronous motors on the slowest speed class is clearly evident where this class showed the highest failure rate in Part 1. For induction motors, the lowest failure rate was again in the highest speed class. The effects of speed are also evaluated in comparisons to horsepower, causes, and failed component.

TABLE I

	Starts/Day 1	1-10	11-30	>30	Duty Application Continuous	Intermittent	Environment Indoor	Outdoor	Speed (r/min) 0-720	721-1800	3600	Grounding Type Solid	Impedance	Ungrounded
INDUCTION MOTORS														
Number of FLR's	234	58	—	—	274	20	203	91	19	216	59	101	123	70
Sample size (unit yr)	3215.8	756.0	88.4*	8.0*	3480.3	587.8	2485.9	1582.3	313.1	2817.9	1037.2	1909.6	1492.0	666.6
FLR rate (FLR's/unit yr)	0.0728	0.0767	—	—	0.0787	0.0340	0.0817	0.0575	0.0607	0.0766	0.0569	0.0529	0.0824	0.1050
Average hours DT/FLR	61.1	83.8	—	—	57.9	194.0	51.1	96.8	191.2	54.5	48.1	69.2	58.0	71.5
Median hours DT/FLR	12.0	18.0	—	—	12.0	54.0	8.0	48.0	72.0	8.0	36.0	36.0	10.0	8.0
Number of FLR's with no DT given	84	13	—	—	90	7	72	48	0	86	11	37	58	2
SYNCHRONOUS MOTORS														
Number of failures	13	23	2*	—	36	2*	38	—	27	10	1*	12	24	2*
Sample size (unit yr)	194.5	266.1	8.0	—	426.6	42.0	451.2	17.4*	254.9	200.9	12.7	251.7	200.3	16.5
FLR rate (FLR's/unit yr)	0.0668	0.0864	—	—	0.0844	—	0.0842	—	0.1059	0.0498	—	0.0477	0.1198	—
Average hours DT/FLR	97.5	68.4	—	—	58.4	—	74.2	—	33.1	139.1	—	166.0	39.8	—
Median hours DT/FLR	24.0	16.0	—	—	16.0	—	16.0	—	16.0	96.0	—	60.0	16.0	—
Number of FLR's with no DT given	2	1	—	—	16	—	3	—	0	3	—	2	1	—

*Small sample size.

TABLE II
MOTOR TYPE VERSUS SERVICE FACTOR

	Induction 1.0	1.15	>1.15	Synchronous 1.0	1.15	>1.15	Wound Rotor 1.0	1.15	>1.15	Direct Current 1.0	1.15	>1.15
Number of FLR's	127	165	2*	25	10	3*	10	12	—	6*	—	—
Sample size (unit yr)	2062.7	1943.0	62.5	274.2	152.8	41.5	160.7	246.4	—	94.2	30.0*	7.3*
FLR rate (FLR's/unit yr)	0.0616	0.0849	—	0.0912	0.0654	—	0.0622	0.0487	—	—	—	—
Average hours DT/FLR	54.4	75.0	—	81.2	63.4	—	52.3	192.2	—	—	—	—
Median hours DT/FLR	8.0	24.0	—	16.0	20.0	—	24.0	162.0	—	—	—	—
Number of FLR's with no DT given	28	71	—	0	3	—	3	6	—	—	—	—

*Small sample size.

SERVICE FACTOR

Another interesting result of this survey in Part 1 was that 1.15 service factor (SF) motors had a higher failure rate than 1.0-SF motors. Tables II–IV take a closer look at this category by comparison to other categories.

Table II compares service factor to the various types of motors surveyed. The results show that 1.15-SF induction motors failed more than 1.0-SF induction motors, but the opposite was true with synchronous and wound rotor induction motors. The lowest failure rate of all was in 1.15-SF wound rotor induction motors.

In Table III the service factor is evaluated in horsepower classes. Only the first two size classes had adequate response. As in the results of Part 1 failure rate increased with increase in service factor in the smallest size class. However, in the next larger size class the failure rate was approximately the same for 1.0 and 1.15 SF.

The next category broken out with service factor is voltage, shown in Table IV. The same trend evident in Part 1 is again evident here. The failure rate increased with increase in service factor for each voltage class where response was adequate. The service factor is evaluated further in Table VIII with comparisons to failed component and causes.

SPEED

Part 1 of the survey results showed a decrease in failure rate with increase in speed rating for all categories. Most expect that failure rate with speed is most affected by motor size. Table V is presented to show these categories from this survey. The results show the same trend as Part 1 except for a slight deviation in the smallest motor class. The 721–1800

TABLE III
HORSEPOWER VERSUS SERVICE FACTOR

	201–500 hp			501–5000 hp			5001–10 000 hp			10 000 hp		
	1.0	1.15	>1.15	1.0	1.15	>1.15	1.0	1.15	>1.15	1.0	1.15	>1.15
Number of failures	105	114	—	56	71	5*	7*	2*	—	—	—	—
Sample size (unit yr)	1758.0	1405.9	34.1*	777.4	961.4	77.2	39.2	4.8	—	17.2*	—	—
FLR rate (FLR's/unit yr)	0.0597	0.0811	—	0.0720	0.0739	—	—	—	—	—	—	—
Average hours DT/FLR	47.7	'48.6	—	86.8	126.5	—	—	—	—	—	—	—
Median hours DT/FLR	8.0	12.0	—	16.0	50.0	—	—	—	—	—	—	—
Number of FLR's with no DT given	21	50	—	11	29	—	—	—	—	—	—	—

*Small sample size.

TABLE IV
VOLTAGE VERSUS SERVICE FACTOR

	0–1000 V			1001–5000 V			5001–15 000		
	1.0	1.15	>1.15	1.0	1.15	>1.15	1.0	1.15	>1.15
Number of FLR's	54	46	—	107	139	5*	8	1*	—
Sample size (unit yr)	745.5	509.0	7.3*	1725.4	1837.5	104.0	121	25.6	—
FLR rate (FLR's/unit yr)	0.0724	0.0904	—	0.0620	0.0756	—	0.0661	—	—
Average hours DT/FLR	38.8	88.3	—	75.3	75.9	—	22.7	—	—
Median hours DT/FLR	8.0	36.0	—	16.0	16.0	—	24.0	—	—
Number of FLR's with no DT given	6	18	—	24	61	—	2	—	—

*Small sample size.

TABLE V
HORSEPOWER VERSUS SPEED (r/min)

	201–500 hp			501–5000 hp			5001–10 000 hp			>10 000 hp		
	0–720	721–1800	3600	0–720	721–1800	3600	0–720	721–1800	3600	0–720	721–1800	3600
Number of FLR's	19	157	43	38	75	19	7*	2*	—	—	—	—
Sample size (unit yr)	277.3	2209.8	711.0	400.1	940.0	475.8	39.2	4.8	—	9.7*	7.5*	—
FLR rate (FLR's/unit yr)	0.0685	0.0710	0.0605	0.0950	0.0798	0.0399	—	—	—	—	—	—
Average Hours DT/FLR	156.2	35.7	39.9	99.4	109.2	116.1	—	—	—	—	—	—
Median Hours DT/FLR	70.0	8.0	36.0	16.0	24.0	52.0	—	—	—	—	—	—
Number of FLR's with no DT given	5	58	8	0	36	4	—	—	—	—	—	—

*Small sample size.

TABLE VI
ENCLOSURES—OUTDOOR

	Open	Weather Protected	Totally Enclosed (TEFC, E.P., D.I.P.)	Totally Enclosed (Open Pipe Vent)	Totally Enclosed (Water-Air)	Totally Enclosed (Air-Air)
Number of FLR's	18	17	49	2[a]	—	11
Sample size (unit yr)	111.1	379.0	1014.7	16.0	—	131.7
FLR rate (FLR's/unit yr)	0.1620	0.0449	0.0483	—	—	0.0835
Average hours DT/FLR	119.1	179.6	69.4	—	—	23.9
Median hours DT/FLR	48.0	80.0	48.0	—	—	12.0
Number of FLR's with no DT given	9	2	14	—	—	4
Failed component[b]						
Bearing	11	6	28	1	—	4
Winding	5	3	16	—	—	7
Rotor	1	1	2	—	—	—
Shaft or coupling	—	2	4	—	—	—
Brushes or slip rings	—	—	—	1	—	—
External dev.	—	3	—	—	—	—
Not specified	1	2	—	—	—	—

[a] Small sample size.
[b] Some respondents reported more than one failed component per failure.

TABLE VII
ENCLOSURES—INDOOR

	Open	Weather Protected	Totally Enclosed (TEFC, E.P., D.I.P.)	Totally Enclosed (Open Pipe Vent)	Totally Enclosed (Water-Air)	Totally Enclosed (Air-Air)
Number of FLR's	206	8	29	4[a]	6[a]	9
Sample size (unit yr)	2480.8	170.6	312.5	24.7	119.5	229.5
FLR rate (FLR's/unit yr)	0.0830	0.0469	0.0928	—	—	0.0392
Average hours DT/FLR	58.8	48.0	28.9	—	—	106.7
Median hours DT/FLR	16.0	16.0	10.0	—	—	8.0
Number of FLR's with no DT given	62	1	14	—	—	2
Failed component[b]						
Bearing	96	1	14	2	—	5
Winding	47	—	5	—	—	3
Rotor	3	—	2	—	—	—
Shaft or coupling	11	2	—	1	—	—
Brushes or slip rings	12	—	—	1	1	—
External dev.	6	4	—	—	4	—
Not specified	32	1	8	—	1	1

[a] Small sample size.
[b] Some respondents reported more than one failed component per failure.

r/min motors show a slightly higher failure rate than the 0–720 r/min motors. An interesting result is that the highest speed larger motors failed only approximately one-half the rate of the slowest speed smaller motors.

ENCLOSURES VERSUS ENVIRONMENT

Unexpected results of Part 1 were the relative failure rates of open and enclosed motors and the relative failure rates of indoor and outdoor motors. To evaluate these results further, the categories are combined in Tables VI and VII with failed components also included.

Table VI shows the highest failure rate with open type motors as would be expected since the environment is outdoor. In Table VII it was the second class of enclosed motors, which includes TEFC, explosion-proof (E.P.), and dust ignition proof (D.I.P.), with the highest failure rate. Combining all enclosed classes in each table shows very little difference in failure rate between indoor enclosed motors and outdoor enclosed motors.

TABLE VIII
SPEED AND SERVICE FACTOR VERSUS FAILED COMPONENT AND CAUSES[a]

	Service Factor			Speed (r/min)		
	1.0	1.15	>1.15	0–720	721–1800	3600
Failed Component[b]						
Bearing	47.8	39.6	40	21.1	46.2	56.5
Winding	27.8	24.8	—	29.6	25.9	21.7
Rotor	2.8	5.0	—	8.5	2.0	5.8
Shaft or Coupling	6.7	6.4	—	5.6	6.9	5.8
Brushes or slip ring	7.2	1.5	—	15.5	2.0	—
External Device	0.6	6.4	60	8.5	2.8	5.8
Not Specified	7.2	16.3	—	11.3	14.2	4.3
Total FLR's	180	202	5	71	247	69
Failure initiator						
Transient Overvoltage	2.5	0.6	—	1.6	0.5	1.8
Overheating	15.2	11.2	20.0	8.1	13.5	17.9
Other Insulation Breakdown	12.7	12.8	—	12.9	14.4	5.4
Mechanical Breakage	36.7	30.2	20.0	16.1	36.0	41.1
Electrical Fault	10.1	3.9	60.0	12.9	6.8	5.4
Stalled Motor	1.3	0.6	—	3.2	—	1.8
Other	21.5	40.8	—	45.2	28.8	26.8
Total FLR's	158	179	5	62	222	56
Failure contributor						
Persistent Overloading	5.7	3.3	—	4.8	5.1	—
High-Ambient Temperature	5.7	1.1	—	1.6	3.3	3.8
Abnormal Moisture	7.1	4.9	—	4.8	6.5	3.8
Abnormal Voltage	2.1	1.1	—	1.6	0.9	3.8
Abnormal Frequency	—	1.1	—	—	4.7	1.9
High Vibration	14.2	16.8	—	14.5	14.9	18.9
Aggressive Chemicals	7.1	2.2	—	3.2	5.1	1.9
Poor Lubrication	19.9	10.9	40.0	9.7	14.4	24.5
Poor Ventilation or Cooling	2.1	4.9	—	8.1	2.8	1.9
Normal Deterioration/Age	17.0	33.2	60.0	25.8	28.8	18.9
Other	19.1	20.1	—	25.8	17.7	20.8
Total FLR's	141	184	5	62	215	53
Failure underlying cause						
Defective Component	12.9	25.6	60.0	19.4	19.6	23.1
Poor Installation/Testing	12.9	13.5	—	4.8	14.4	17.3
Inadequate Maintenance	22.4	20.5	20.0	16.1	25.8	11.5
Improper Operation	2.0	5.1	—	4.8	2.6	5.8
Improper Handling/Shipping	0.7	0.6	—	—	1.0	—
Inadequate Physical Protection	10.9	1.9	—	3.2	6.7	7.7
Inadequate Electrical Protection	9.5	3.2	—	4.8	6.7	5.8
Personnel Error	4.1	7.7	20.0	11.3	4.1	7.7
Outside Agency-Not Personnel	5.4	2.6	—	8.1	3.6	—
Motor-Driven Equipment Mismatch	4.1	5.8	—	8.1	4.6	1.9
Other	15.0	13.5	—	19.4	10.8	19.2
Total FLR's	147	156	5	62	194	52

[a] Number of failures in percent.
[b] Some respondents reported more than one failed component per failure.

The failed components followed the general overall trend with bearings and windings failing most, with bearings predominant. Only in the last enclosure class of outdoor motors was the trend between bearings and windings reversed.

FAILED COMPONENT AND CAUSES

Table VIII takes the speed analysis a step further by showing the failed components and causes of failure reported for the speed classes. With failed components distributed between the speed classes, the slowest speed motors show windings as the leading failed component and an increase in bearing failure percentages with increasing speed rating. Under causes an interesting result is the relative low percent blamed on inadequate maintenance for the highest speed rating. Also, deterioration from age was less for this class. This supports the low failure rate for high-speed motors.

Table VIII also breaks down service factor with failed component and causes. Bearings again led all components in failures with windings second. There seems to be no real outstanding difference in causes between 1.0 and 1.15 SF. However one difference that undoubtedly contributed to the failure rate of 1.15-SF motors is the contributing cause of

TABLE IX
CAUSES VERSUS VARIOUS CATEGORIES*

	Type		Grounding			Components	
	Induction	Synchronous	Solid	Impedence	Ungrounded	Bearings	Windings
Failure initiator							
Transient overvoltage	1.4	—	0.9	1.4	2.4	—	4.1
Overheating	14.7	—	14.0	11.7	14.5	12.4	21.4
Other insul. breakdown	11.9	21.1	16.7	11.0	9.6	1.9	36.7
Mechanical breakage	37.4	5.3	31.6	26.2	47.0	50.3	10.2
Electrical fault	5.8	23.7	8.8	4.8	10.8	3.7	11.2
Stalled motor	0.7	2.6	—	0.7	2.4	—	2.0
Other	28.1	47.4	28.1	44.1	13.3	31.7	14.3
Total FLR's	278	38	114	145	83	161	98
Failure contributor							
Persistent overload	4.9	2.7	4.5	4.4	3.7	1.4	6.5
High ambient temperature	3.4	—	3.6	0.7	6.1	.7	7.6
Abnormal moisture	6.7	2.7	8.0	4.4	4.9	2.7	18.5
Abnormal voltage	1.5	2.7	—	2.2	2.4	—	5.4
Abnormal frequency	0.7	—	0.9	0.7	—	—	1.1
High vibration	17.6	5.4	16.1	13.2	18.3	21.8	8.7
Aggressive chemicals	4.5	2.7	1.8	4.4	7.3	5.4	6.5
Poor lubrication	16.9	8.1	5.4	16.2	26.8	31.3	5.4
Poor ventilation or cooling	2.2	2.7	8.0	—	3.7	—	7.6
Normal deterioration/age	24.0	51.4	33.9	30.9	9.8	20.4	18.5
Other	17.6	21.6	17.9	22.8	17.1	16.3	14.1
Total FLR's	267	37	112	136	82	147	92
Failure underlying cause							
Defective component	20.3	22.2	23.5	14.5	24.4	17.8	10.9
Poor install/testing	15.9	—	7.8	12.9	19.5	14.5	10.9
Inadequate maintenance	22.8	11.1	25.5	18.5	20.7	27.6	19.6
Improper operation	3.3	2.8	3.9	4.0	2.4	2.0	6.5
Improper handling/shipping	.8	—	1.0	0.8	—	0.7	—
Inadequate physical protection	6.5	2.8	2.9	7.3	8.5	7.9	7.6
Inadequate electrical protection	5.3	11.1	6.9	6.5	4.9	2.6	15.2
Personnel error	5.7	5.6	3.9	6.5	8.5	7.2	5.4
Outside agency-not personnel	2.8	13.9	3.9	4.8	2.4	2.0	3.3
Motor-driven equip. mismatch	4.9	—	5.9	6.5	1.2	5.9	4.3
Other	11.8	30.6	14.7	17.7	7.3	11.8	16.3
Total FLR's	246	36	102	124	82	152	92

* Number of failures in percent.

normal deterioration from age which is about twice that for 1.0-SF motors.

Table IX is somewhat of a mix of some of the interesting categories brought out in other tables with emphasis on causes. Comparing induction and synchronous motors is difficult here because of the overwhelming response of induction motors. However, some of the results of other categories are supported. For instance, continuous duty induction motors had a higher failure rate than intermittent duty induction motors. Aside from the obvious influence of mechanical breakage, overheating and insulation breakdown are supportive. The contributing cause of normal deterioration from age is also evident.

The table correlates bearing and winding failures with causes rather well. Additionally, underlying causes show that both defective component and inadequate maintenance were reported as major factors in bearing and winding failures with inadequate maintenance the most significant. Failure initiators and contributors follow a reasonably logical trend.

The trend in failure rates for the categories of grounding do not appear supportive in this table if voltage related causes are expected to be obvious. This category exemplifies others where causes do not correlate well. It seems that in these results bearing and winding failures (especially bearing failures) and their related causes obscure some of the other cause reasoning.

MAINTENANCE

Tables X–XII attempt to delve further into the effects of maintenance on failure data. Table X reveals when the failed components were discovered. It gives some correlation to the effect of maintenance since one would expect a significant number of failures to be discovered during maintenance or testing under a good maintenance program. One observation for these data is that 56 percent of the bearing failures were discovered during normal operation. This is supported reasonably well by Table IX which shows inadequate maintenance as significant. Except for brushes and slip rings, all failed components show an obvious greater percentage of discovery during normal operation.

Tables XI and XII are presented to take a closer look at the underlying cause, inadequate maintenance, and associated failure data blamed on this cause. Again bearings by far led all other components in failures. Approximately 25 percent of all

TABLE X
FAILED COMPONENT VERSUS TIME DISCOVERED[a]

Failed Component[b]	Time Discovered: Normal Operation	Maintenance or Test	Other
Bearing	36.6	60.6	50.0
Winding	33.1	8.3	28.6
Rotor	5.1	1.8	—
Shaft or coupling	5.8	8.3	14.3
Brushes or slip rings	3.1	7.3	—
External device	5.1	3.7	—
Not specified	11.3	10.1	7.1
Total FLR's	257	109	14

[a] Number of failures in percent.
[b] Some respondents reported more than one failed component per failure.

TABLE XI
INADEQUATE MAINTENANCE
FAILED COMPONENTS AND CAUSES[a]

Failed component[b]	
Bearing	59.6
Winding	25.4
Rotor	1.4
Shaft or coupling	—
Brushes or slip ring	8.5
External device	1.4
Other	4.2
Total FLR's	71
Failure initiator	
Transient overvoltage	—
Overheating	4.2
Other insulation breakdown	14.1
Mechanical breakage	52.1
Electrical fault	2.8
Stalled motor	—
Other	26.8
Total FLR's	71
Failure contributor	
Persistent overloading	—
High ambient temperature	4.2
Abnormal moisture	7.0
Abnormal voltage	—
Abnormal frequency	—
High vibration	4.2
Aggressive chemicals	9.9
Poor lubrication	43.7
Poor ventilation/cooling	1.4
Normal deterioration/age	18.3
Other	11.3
Total FLR's	71

[a] Number of failures in percent.
[b] Some respondents reported more than one failed component per failure.

TABLE XII
INADEQUATE MAINTENANCE FAILURE DATA

Number of FLR's	66
Sample size (unit yr)	603.6
FLR rate (FLR's/unit yr)	0.1093
Average hours DT/FLR	80.8
Median hours DT/FLR	9.0
Number of FLR's with no DT given	13
Maintenance quality and cycle	**Number of FLR's (percent)**
Excellent	
< 12 mo	25.8
12–24 mo	—
> 24 mo	—
Fair	
< 12 mo	37.9
12–24 mo	7.6
> 24 mo	3.0
Poor	
< 12 mo	3.0
12–24 mo	12.1
> 24 mo	—
Total FLR's	66

bearing failures were reported due to inadequate maintenance. Close to 44 percent of the brush and ship ring failures were reported due to this cause which does not follow well from Table X. The single largest contributor with this underlying cause is poor lubrication.

Table XII shows a definite higher failure rate for inadequate maintenance related failures than the Part 1 failure rates for maintenance quality. In Part 1 the failure rate results for excellent to poor maintenance ranged from 0.0708 to 0.0797, respectively.

Data for when failures were discovered versus maintenance quality are presented in Table XIII. It was expected that the fair and excellent categories would be significantly different in when failures were discovered, but the results show very little difference. The same table also includes months since last maintenance versus maintenance quality. The failures seem to follow the same trend as scheduled cycle reported with most occurring less than 12 mo since maintenance. This table is presented in the same format as [2, table 70]. Those results showed an obvious difference between fair and excellent maintenance overall. The trend in failures was to a certain degree increasing directly with months since maintenance and indirectly with maintenance quality. The new survey results here show a very different trend with most failures occurring where last maintenance was less than 12 mo prior to the failure.

GENERAL DISCUSSION

The additional comparisons and analyses made in this paper have supported results of Part 1 in some cases and in other cases have revealed results that were obscured in the general categorical tables of Part 1. Not all questions are answered here, and there are certainly many more categories and comparisons that can be made with the data of this survey. As examples, bearing and winding failures compared to starts per

TABLE XIII
MAINTENANCE QUALITY VERSUS TIME FAILURES DISCOVERED AND MONTHS SINCE MAINTENANCE*

Maintenance Quality	Time Discovered: Normal Operation	Maintenance or Test	Other	Months Since Maintenance: < 12	12–24	> 24
Excellent	85	35	1	87	17	6
Fair	132	63	10	102	22	8
Poor	15	3	1	11	5	—
None	7	—	—	—	1	5
Total	239	101	12	200	45	19
Inadequate Maintenance Cause						
Excellent	5	12	—	17	—	—
Fair	22	8	2	16	1	1
Poor	8	1	1	4	1	—
None	7	—	—	—	1	5
Total	42	21	3	37	3	6

* Number of failures.

day and duty application could add meaning to the results. The Reliability Subcommittee is presently evaluating criteria that should be presented in a third set of results, Part 3. Interested readers should submit comments and suggestions on information they would like to see in Part 3. In the format presented in these results, bearing failures and their causes were very dominant and likely prevent other less significant correlations to be evident.

ACKNOWLEDGMENT

The Reliability Subcommittee acknowledges and expresses its appreciation to J. Rizo and W. H. Healy of El Paso Natural Gas Company for assistance in the computer program used for the analysis of the data for this presentation.

REFERENCES

[1] IEEE Committee Report, "Report of large motor reliability survey of industrial and commercial installations, Part I," in *1983 IEEE I&CPS Conference Record*; also *IEEE Trans. Ind. Appl.*, vol. IA-21, pp. 853–864, July/Aug. 1985.

[2] IEEE Committee Report, "Report on Reliability Survey of Industrial Plants, Part VI—Maintenance Quality of Electrical Equipment," in IEEE Standard 493, 1980.

Pat O'Donnell (S'64–M'68–SM'80), for a photograph and biography, please see page 864 of this issue.

Report of Large Motor Reliability Survey of Industrial and Commercial Installations: Part 3

MOTOR RELIABILITY WORKING GROUP
POWER SYSTEMS RELIABILITY SUBCOMMITTEE
POWER SYSTEMS ENGINEERING COMMITTEE
INDUSTRIAL & COMMERCIAL POWER SYSTEMS DEPARTMENT
IEEE INDUSTRY APPLICATIONS SOCIETY

***Abstract*—Results of a survey conducted in 1982 of the reliability of large motors have been presented and published in two parts [1], [2]. These results have generated numerous questions and comments and, consequently, the need to further analyze the data of the survey was recognized. Part 1 presents general results based on categories of motor types and applications specifically requested in the survey questionnaire. Part 2 combines various categories and addresses some questions resulting from Part 1. Part 3 of the survey results is presented here to address new questions and comments and to add more specific analyses of areas not yet explored. These results, along with Parts 1 and 2, provide the complete complement of analysis to date.**

Introduction

THE THIRD part of the results of the 1982 survey of reliability of large motors is presented here and summarized in Tables I through VII. As with Part 2, these results focus on new comparisons of the data. The tables address some questions and comments received since presentation of Part 2 and provide additional analysis of causes. The order of the tables as presented is more or less random and there is no intent to portray a delibrate order.

As in Parts 1 and 2, where no data is given, there is insufficient response to the questionnaire. An asterisk represents failures reported but with insufficient number (less than eight) for credible results. Additionally it is again emphasized that the tables and corresponding discussions represent results of the survey and that there is no intent to draw definite conclusions. Finally, as in Parts 1 and 2, differences in total failures between the various categories of Part 3 reflect missing data from some survey responses.

Paper ICPSD 86-13, approved by the Power Systems Engineering Committee of the IEEE Industry Applications Society for presentation at the 1986 Industrial and Commercial Power Systems Technical Conference, Philadelphia, PA, September 8–11. Manuscript released for publication September 9, 1986.

Members of the IEEE Motor Reliability Working Group
C. Heising is with Industrial Reliability Technology, 216 Farwood Road, Philadelphia, PA 19151.
P. O'Donnell, *Coordinating Author*, is with the El Paso Natural Gas Company, P. O. Box 1492, El Paso, TX 79978.
C. Singh is with the Department of Electrical Engineering, Texas A&M University, College Station, TX 77843.
S. J. Wells is at 1743 Lake Oak Drive, Seabrook, TX 77586.
IEEE Log Number 8612073.

Enclosure—Indoor and Outdoor

Tables I and II are presented to take a closer look at the causes of failures reported for various enclosures in both indoor and outdoor environments. As was evident in the previously published results, most indoor applications were "open" motors and most outdoor applications were totally enclosed fan-cooled (TEFC), explosion-proof or dust ignition-proof motors.

For the outdoor motors with the above enclosures, Table I shows that the major failure initiators are well supported by the failure contributors. The main underlying causes point to defective components and inadequate maintenance. For indoor open motors in Table II, failure initiators and failure contributors again match, but inadequate maintenance was by far the single largest underlying cause.

Comparison of indoor and outdoor environments also reveals certain opposite trends relative to causes of all failures (Part 1, Table 13). For instance, the following causes show opposite trends between indoor and outdoor applications when their respective percentages of total are compared to the same for all applications of Part 1, Table 13: mechanical breakage, electrical fault or malfunction, abnormal moisture, poor lubrication, inadequate electrical protection, inadequate maintenance, and personnel error. An example will make this more clear. For outdoor motors, mechanical breakage is 26/90 or 28.9 percent of the total number of failures for "failure initiator," while for all applications 113/341 is 33.1 percent of the number of failures for "failure initiator." Indoor motors show 85/240, or 35.4 percent versus 33.1 percent.

High Vibration Cause

Tables III and IV present additional results to Parts 1 and 2 for failures blamed on vibration. Table III shows 48 failures blamed on vibration where data are also available on failure initiator and underlying cause. As would be expected, most failures were initiated by mechanical breakage. It is interesting that most underlying causes were reported as defective component and poor installation or testing. Only three failures list inadequate maintenance as a contributing cause. For

TABLE I
ENCLOSURES—OUTDOOR
(No. of Failures)

Causes	Open	Weather-protected	Totally Enclosed TEFC, Exp., D.I.	Totally Enclosed Open Pipe Vent	Totally Enclosed Water-Air	Totally Enclosed Air-Air	Total	All Applications (Part I)
Failure Initiator								
Transient overvoltage	1	—	1	—	—	—	2	5
Overheating	2	4	9	—	—	—	15	45
Other insulation breakdown	4	1	10	1	—	—	16	42
Mechanical breakage	6	7	11	1	—	1	26	113
Electrical fault/malfunction	1	—	4	—	—	4	9	26
Stalled motor	—	—	1	—	—	—	1	3
Other	4	6	5	—	—	6	21	107
Failure Contributor								
Persistent overload	—	2	—	—	—	—	2	14
High ambient temperature	—	1	1	—	—	—	2	10
Abnormal moisture	2	2	5	—	—	—	9	19
Abnormal voltage	2	—	—	—	—	—	2	5
Abnormal frequency	—	—	—	—	—	—	—	2
High vibration	1	3	6	—	—	1	11	51
Aggressive chemicals	1	—	1	1	—	3	6	14
Poor lubrication	—	2	3	—	—	1	6	50
Poor ventilation/cooling	—	—	—	—	—	4	4	13
Normal deterioration/age	2	2	7	1	—	2	14	87
Other	2	5	9	—	—	—	16	65
Failure Underlying Cause								
Defective component	3	4	9	—	—	2	18	62
Poor installation/testing	2	3	4	—	—	—	9	40
Inadequate maintenance	3	2	7	1	—	—	13	66
Improper operation	—	—	—	—	—	1	1	11
Improper handling	1	—	—	—	—	—	1	2
Inadequate physical protection	4	2	—	—	—	—	6	19
Inadequate electrical protection	2	2	3	1	—	—	8	18
Personnel error	—	—	1	—	—	1	2	21
Outside agency-not pers.	—	—	—	—	—	2	2	12
Motor–load mismatch	—	1	1	—	—	3	5	15
Other	—	3	9	—	—	2	14	43

convenience, the total of 51 failures blamed on high vibration (Part 1) is also shown.

Table IV compares vibration failure causes to size. Only two size ranges have sufficient response to allow meaningful results. The table shows that the percent of vibration failures to total failures increases slightly with size.

Starts/Day Versus Continuous Duty Application

The results in Table V attempt to further evaluate the effects of starting on failures. Only continuous duty applications are considered, to avoid confusion over trying to distinguish between various degrees of intermittent duty. The first two voltage classes of induction motors, in which most of the survey data were collected, are emphasized. Also, very little data were collected for the categories of more than ten starts per day.

As can be seen from the table, overall there is very little difference in failure rates between less-than-one and one-to-ten starts per day, and very little difference between the two voltage classes. There does, however, seem to be a trend in longer downtimes for the one-to-ten starts per day category, suggesting that failures were more severe.

Downtime Versus Repair Urgency and Time Discovered

Downtime is expected to be affected by the urgency with which repairs are made and also by when failures are discovered, which would seem to affect the severity of failures. Table VI compares downtime with these categories to get a different view than Parts 1 and 2 provide. Overall the trend in number of failures decreases as downtime increases. There are some obvious deviations from this trend at the range of 51–100 h downtime per failure. Also this trend is obscure under the repair urgency "round-the-clock." It is interesting that for this category there are practically as many failures in the higher downtime ranges as in the lower downtime ranges. Another somewhat unexpected result is that there is no obvious difference in the distribution of failures between the categories under the heading "time discovered." However, the results show that failures corrected by "replace with spare" are predominantly in the least downtime range, as would be expected.

Horsepower Versus Speed: Induction Motors

A recent motor reliability survey [3] sponsored by the Electric Power Research Institute (EPRI) and conducted by the

TABLE II
ENCLOSURES—INDOOR
(No. of Failures)

Causes	Open	Weather-protected	Totally Enclosed TEFC, Exp., D.I.	Totally Enclosed Open Pipe Vent.	Totally Enclosed Water-Air	Totally Enclosed Air-Air	Total
Failure Initiator							
Transient overvoltage	3	—	—	—	—	—	3
Overheating	25	—	3	—	1	1	30
Other insulation breakdown	22	—	3	—	1	1	27
Mechanical breakage	68	1	11	2	—	3	85
Electrical fault/malfunction	—	5	1	—	—	3	9
Stalled motor	—	—	—	—	—	—	—
Other	68	1	10	2	4	1	86
Failure Contributor							
Persistent overload	—	—	3	—	—	1	4
High ambient temperature	—	—	3	—	—	1	4
Abnormal moisture	10	—	—	—	—	—	10
Abnormal voltage	—	—	—	—	—	—	—
Abnormal frequency	—	—	—	—	—	—	—
High vibration	35	1	1	—	—	2	39
Aggressive chemicals	—	1	—	1	—	—	2
Poor lubrication	38	—	3	—	1	2	44
Poor ventilation/cooling	—	1	—	2	1	—	4
Normal deterioration/age	38	3	14	1	—	3	59
Other	38	1	5	—	4	—	48
Failure Underlying Cause							
Defective component	27	4	6	1	5	—	43
Poor installation/testing	28	—	1	—	—	1	30
Inadequate maintenance	41	1	8	1	—	2	53
Improper operation	—	—	1	—	—	1	2
Improper handling	—	—	—	—	—	—	—
Inadequate physical protection	10	—	1	1	—	1	13
Inadequate electrical protection	—	1	—	—	—	2	3
Personnel error	16	—	—	—	—	1	17
Outside agency—not pers.	7	—	1	1	1	—	10
Motor-load mismatch	9	—	1	—	—	—	10
Other	23	1	4	—	—	1	29

TABLE III
VIBRATION FAILURES
(No. of Failures)

Failure Initiator	Transient overvoltage	0
	Overheating	6
	Other insulation breakdown	2
	Mechanical breakage	23
	Electrical fault/malfunction	3
	Stalled motor	1
	Other	13
Failure Underlying Cause	Defective component	14
	Poor installation/test.	15
	Inadequate maintanance	3
	Improper operation	0
	Improper handling/shipping	1
	Inadequate physical protection	3
	Inadequate electrical protection	0
	Personnel error	4
	Outside agency—not pers.	0
	Motor-load mismatch	3
	Other	5
Total Vibration Failures (From Part I)		51

TABLE IV
VIBRATION FAILURES VERSUS SIZE

Motor Size	No. of Vibration Failures	Total No. Of Failures—All Causes	Percent
201-500 hp	27	218	12.4
501-5000 hp	22	131	16.8
5001-10 000 hp	1	9	*
< 10 000 hp	—	—	—

* Small sample size.

TABLE V
STARTS PER DAY VERSUS CONTINUOUS DUTY

	No. of Starts Per Day	No. of Flrs	Total Population U-Yrs	Flr Rate	Avg. Hrs D.T./Flr	Med Hrs D.T./Flr
All Motors	< 1	241	3111.6	0.0775	48.7	12
	1-10	90	1178.1	0.0764	90.8	16
0-1000 V	All motors					
	< 1	71	854.5	0.0831	36.1	8
	1-10	22	244.5	0.0900	111.1	48
	Individual Motors					
	< 1	68	768.7	0.0885	37.2	8
	1-10	13	148.4	0.0876	50.7	36
1000-5000 V	All motors					
	< 1	163	2185.0	0.0746	55.7	12
	1-10	66	859.1	0.0768	83.6	16
	Individual Motors					
	< 10	152	1876.9	0.0810	54.7	12
	1-10	38	497.0	0.0765	102.6	16

TABLE VI
DOWNTIME VERSUS REPAIR URGENCY AND TIME DISCOVERED
(No. of Flrs)

	Repair Urgency				Time Discovered		
Downtime Per Flr. (Hours)	Normal Working Hours	Round the Clock	Replace with Spare	Low Priority	During Normal Operation	During Maintenance or Test	Other
1-12	14	2	89	—	66	35	4
13-24	32	13	9	—	35	20	—
25-50	10	6	2	—	12	6	—
51-100	13	11	2	—	20	6	—
101-150	6	6	—	—	12	—	—
151-200	4	4	1	1	5	4	2
201-350	3	3	1	3	7	3	—
< 350	5	—	1	2	8	1	—

TABLE VII
HORSEPOWER VERSUS SPEED
INDUCTION MOTORS

	No. of Failures	Unit Years	Failure Rate
0-720 r/min			
201-500 hp	7	137.92	0.0508
501-5 000 hp	12	175.16	0.0685
5001-10 000 hp	—	—	—
> 10 000 hp	—	—	—
721-1800 r/min			
201-500 hp	148	1922.43	0.0770
501-5000 hp	66	740.1	0.0892
5001-10 000 hp	1	2.83	
> 10 000 hp	—	7.5	—
3600 r/min			
201-500 hp	42	655.75	0.0640
501-5 000 hp	16	358.66	0.0446
5001-10 000 hp	—	—	—
> 10 000 hp	—	—	—

* Small sample size.

General Electric Company focused on electric utility powerhouse motors. Several interesting correlations between the EPRI survey and the IEEE survey emerged. In a Discussion [4] of Part 1 of the IEEE results by participants in the EPRI survey it was noted that hp per pole had been analyzed in past studies as affecting failure rate. The data in the IEEE survey did not allow this specific analysis. Table VII, presented here, is a more general representation of this subject, showing ranges of speed and of size. Induction motors are the most common type in use and consequently most survey data were collected for this type. Table VII has been limited to induction motors. It should be noted that this table was also published in the Closure to the Discussion referenced in the aforementioned. Similar results were published in Part 2, Table 5, but included all types of motors surveyed.

The highest failure rate appears in the middle speed range and at 501-5000 hp. One might observe that within the first two speed ranges, as hp per pole increases (assuming that, specifically, 720 r/min and 1800 R/min are predominant in these speed ranges) so also does failure rate. However, the highest speed range reverses this trend. Aside from this observation there is not a significant difference in failure rates between the different horsepower ranges within the first two

speed ranges. Table 5 of Part 2, which included all motor types surveyed, showed similar trends.

General Discussion

The results of Part 3 have presented several new aspects of the data. Most are a result of questions and comments received concerning Parts 1 and 2, but in some cases the data did not allow exact analysis. In some cases trends are evident and in some cases they are not. Some of the results expected or at least anticipated, for example, were that most failures occurred with lower downtime per failure, high vibration resulted in mechanical breakage, and longer downtime per failure occurred with induction motors starting more than once per day. Some of the interesting results were the opposite trends in causes of failures between indoor and outdoor applications and vibration causes being blamed mostly on defective component and poor installation or testing.

Overall, Part 3 has added credibility to some previously published results and has reinforced some areas of causes that are otherwise normally speculated.

References

[1] Pat O'Donnell, Coordinating Author, "Report of large motor reliability survey of industrial and commercial installations—Part 1," IEEE Committee Report, in IEEE Trans. Ind. Appl., vol. IA-21, no. 4, pp. 853-864, July/Aug. 1985.

[2] Pat O'Donnell, Coordinating Author, "Report of large motor reliability survey of industrial and commercial installations—Part 2," IEEE Committee Report, in IEEE Trans. Ind. Appl., vol. IA-21, no. 4, pp. 865-872, July/Aug. 1985.

[3] P. F. Albrecht, J. C. Appiarius, R. M. McCoy, E. L. Owen, and D. K. Sharma, "Assessment of the reliability of motors in utility applications—Updated," IEEE Trans. Energy Conversion, vol. EC-1, no. 1, pp. 39-46, March 1986.

[4] E. L. Owen, Discussion of "Report of large motor reliability survey of industrial and commercial installations—Part 1," IEEE Trans. Ind. Appl., vol. IA-21, no. 4, pp. 863-864, July/Aug. 1985.

Discussion

Richard Bloss *(Independent Consultant, #5462 Banbury Drive, Cleveland, OH 44139, formerly with Booz, Allen & Hamilton):* I applaud the IEEE Motor Reliability Working Group for their efforts to build a better understanding of the factors that influence large motor reliability. I would like to add that my remarks here are my own and not those of the Electric Power Research Institute, the General Electric Company, the prime contractor for the EPRI study, or of Booz, Allen & Hamilton, the subcontractor for the survey phase.

There are certain differences in the focus of the two studies that are important to understand. The EPRI study was looking at power generation plant applications. The IEEE was looking at a much broader commercial and industrial application base. To capitalize on the commonality of applications, the EPRI study focused on possible effects of applications as well as basic motor failure modes. The EPRI study permits conclusions to be drawn across similar applications.

The General Electric Company representatives may have already drawn what may be the most significant conclusion to the EPRI study in earlier remarks they made relating to the first part of the IEEE study. That conclusion is that the most significant variable in motor reliability in the EPRI study was "who was the owner." My personal analysis of the findings leads me to draw the conclusion that those utilities which had developed their own motor specifications over and beyond the industry standards had the best reliability history.

As a result of the larger sample in the EPRI study and the greater focus on a limited range of applications, more conclusions can be drawn relating to applications. As an example, in the EPRI study a problem was identified relating to the failure of Weatherproof II enclosures to protect motors in outdoor installations in coastal regions affected by severe weather. In another case, a pattern of motor misapplication in purchased subsystems was identified. Data from a number of owners of a particular subsystem served to pinpoint the use of motors designed for horizontal use, with adequate axial thrust capacity, in vertical applications. The subsystem supplier had failed to understand the problem of lubrication of the bearings. Owners who had researched the problem of bearing failure were installing their own redesigned lube system while others who were unaware of the root cause were continuing to repair the same bearing failure over and over.

It does appear from the EPRI study that customer-generated specifications can impart a favorable impact on motor reliability. The IEEE may want to pursue, in conjunction with the EPRI and others, a further study of what specific factors in customer-generated motor specifications have this positive effect on motor reliability.

The payoff is clear. In the EPRI study the average cost per year of motor failures was identified as $300 000 per power generating unit. The "best" owners had much lower motor failure costs, approaching *zero* cost. The average unit had just 40 motors. The average cost per motor per year for failures was about $7500, *plus* the cost to repair the motor!

I feel the IEEE Working Group must enlist the help of major customers of large motors to develop improved specifications that will reduce motor failures.

Manuscript released for publication October 9, 1986.

C. R. Heising and Pat O'Donnell: The Discussion by Mr. Bloss presents some additional views and comparisons of the EPRI and IEEE surveys of the reliability of large motors.

A notable difference in the published results from the IEEE survey is the omission of conclusions except for some obvious conclusions from the data. This omission is deliberate and may possibly lead to a false impression that the IEEE results are not conducive to definite conclusions. We believe the results present facts as accurate as can possibly be obtained in a survey conducted by mail. The IEEE survey was successful in obtaining data covering causes of failures, and in some cases this was related to pertinent design factors.

A major difference in the surveys by the EPRI and the IEEE is the population base of each. The EPRI results, based on a large population base, appear to be more complete and contain more detail in some specific areas such as the failed part and the application of the motor. The IEEE survey results are based upon a lesser population, but are more complete on the causes of the failures and the effect of maintenance. The cause data included failure initiating cause, failure contributing cause, and failure responsibility.

Mr. Bloss's comments about the effect that customer-generated specifications can have on improving the reliability of motors are very pertinent. He suggests that the IEEE may want to pursue this subject further and identify some of the most pertinent factors that could be specified in order to improve the reliability of motors. The IEEE-IAS Power Systems Reliability Subcommittee will consider this matter further.

Accurate and well-engineered specifications are certainly found desirable by most users and manufacturers. The inability to provide such specifications may often be caused by insufficient experience and expertise, and this may lead to poor reliability. The IEEE survey results are intended to aid this cause by revealing what is actually happening in the industry, thus allowing improved standards and specifications. These results reveal existing reliability with existing specifications. Mr. Bloss reports from his experience on the EPRI study that good specifications can coincide with good reliability.

The data from the IEEE motor reliability survey will be included in the next revision to IEEE Standard No. 493 (Gold Book), "Recommended Practice for Design of Reliable Industrial and Commercial Power Systems." This recommended practice standard and its future revisions contain much of the data collected in the IEEE equipment reliability surveys of industrial and commercial installations.

Manuscript released for publication October 9, 1986.

Pat O'Donnell (S'64-M'68-SM'80) was born in El Paso, TX in 1942 and received the B.S.E.E. degree from Texas Western College (now University of Texas at El Paso) in 1965.

After brief employment with the Schlumberger Well Surveying Corporation, he joined the El Paso Natural Gas Company in 1966 and is presently a Consultant Electrical Engineer in the main office, Engineering Department, in El Paso.

He is presently active in the Industrial and Commercial Power Systems Department of the IEEE Industry Applications Society and serves as Secretary of the department. He is a Past Chairman of the Power System Technologies Committee and within the Power Systems Engineering Committee he is presently Chairman of the Orange Book (IEEE Std. 446) Working Group in the Emergency and Standby Power Systems Subcommittee, Chairman of the Motor Reliability Working Group in the Power Systems Reliability Subcommittee, and a member of the Power Systems Analysis Subcommittee. He is a Registered Professional Engineer in the States of Texas and New Mexico.

Reliability Study of Cable, Terminations, and Splices by Electric Utilities in the Northwest

By
William F. Braun

IEEE Transactions on Industry Applications
January/February 1987, pp. 144–153

Reliability Study of Cable, Terminations, and Splices by Electric Utilities in the Northwest

WILLIAM F. BRAUN, MEMBER, IEEE

Abstract—**The results for cable, terminations, and splice reliability are summarized from a reliability report prepared annually by the Northwest Electric Light and Power Association (NELPA). Failure rates are given for primary cable, secondary cable, plug-in elbow connectors, primary splices and loadbreak junctions, pole top terminators, and secondary connections. Pertinent factors that affect the failure rates are identified.**

Introduction

FOR THE PAST 18 years the Northwest Underground Distribution Committee[1] of the Northwest Electric Light and Power Association (NELPA) has prepared an annual report titled "URD equipment and materials reliability in the Northwest" [1].

Of particular interest to the IEEE Power Systems Reliability Subcommittee on Industrial and Commercial Power Systems is the portion of the report pertaining to cables, terminations, splices, and connections, since similar equipment is often used on industrial or commercial power systems.

The data in the NELPA report appears to be more complete and represents a much larger sample size than the data from the IEEE reliability survey of industrial plants [2] that was published in 1973–1974 and incorporated into the present ANSI/IEEE Standard No. 493-1980 [3]. The standard is being revised and updated in 1986. This paper will sumarize the NELPA report with the intent of using it as a source for the 1986 revision of ANSI/IEEE Standard No. 493.

Background

NELPA companies serve most of the Northwest areas of the United States. Because the geographical makeup of this area consists of some very wet areas, some very dry areas, some very hot areas, and some very cold areas, the data from the report should be valuable for evaluating URD equipment for use around the country, particularly for such items as corrosion resistance and insulation failure.

NELPA consists of the following member companies.

Idaho Power Company
Montana Power Company
Pacific Power & Light Company
Portland General Electric Company
Puget Sound Power & Light Company
Utah Power & Light Company
Washington Water Power Company

Paper ICPSD 86-14, approved by the Power Systems Engineering Committee of the IEEE Industry Applications Society for presentation at the 1986 Industrial and Commercial Power Systems Technical Conference, Cleveland, OH, May 5-8. Manuscript released for publication September 9, 1986.

W. F. Braun is with the Owens-Corning Fiberglas Corporation, Fiberglas Tower SG14, Toledo, OH 43659.

IEEE Log Number 8612031.

[1] Kenneth W. Prier of Portland General Electric Company was Chairman of the Northwest Underground Distribution Committee in 1984, when Report No. 17 was issued. Richard M. Snell of Montana Power Company is the present Chairman.

TABLE I
CABLE FAILURE RATES—ALL VOLTAGE CLASSES
(Failures per 100 Conductor Miles)

1969	0.67	1977	0.98
1970	1.11	1978	1.47
1971	0.73	1979	1.82
1972	0.91	1980	1.68
1973	1.00	1981	2.55
1974	1.03	1982	2.51
1975	0.89	1983	2.27
1976	1.10		

Failure Data Reporting

The report is only concerned with natural failures of equipment or materials. All failures caused by abnormal external means, such as through dig-ins or damage prior to installation, are not intended to be included in the data. In the cases where the cause of a failure could not be determined, the cause of the failure is assumed and reported in that way.

The member utilities are continuously improving their efforts to accumulate basic data. However, there are still problems with field people not reporting the material failures. All failure rates in this report should be considered on the low side.

Primary Cable

Table I lists the failure record for all voltage classes (15 kV, 25 kV, and 35 kV) and insulation types of primary cable used on the systems.

In general the failure record is excellent, although high molecular weight polyethylene (HMWPE) insulated cable is failing at a much greater rate than crosslinked polyethylene (XLPE). (See Tables IIIA and IIIB for complete data.)

The failure rates for the last few years are high because one utility has just started reporting failures and they have been having problems with 175-mil 15-kV cable.

A comparison was also made between 15-kV HMWPE and 15-kV XLPE cable for the last ten years. (See Table II.)

TABLE II
15-kV CLASS CABLE
(Failures per 100 Conductor Miles of Cable)

Failure Year	175-mil HMWPE	220-mil HMWPE	175-mil XLPE	220-mil XLPE
1973	0.90	1.40	0.27	0.0
1971	0.41	1.41	0.53	0.56
1975	0.72	1.51	0.33	0.0
1976	1.19	1.28	0.47	1.72
1977	1.25	1.04	0.39	0.0
1978	2.07	0.69	1.06	0.08
1979	2.67	0.90	0.68	0.12
1980	3.42	0.65	0.03	0.0
1981	5.38	0.95	0.10	0.05
1982	4.77	1.69	0.07	0.0
1983	4.40	1.73	0.53	0.0

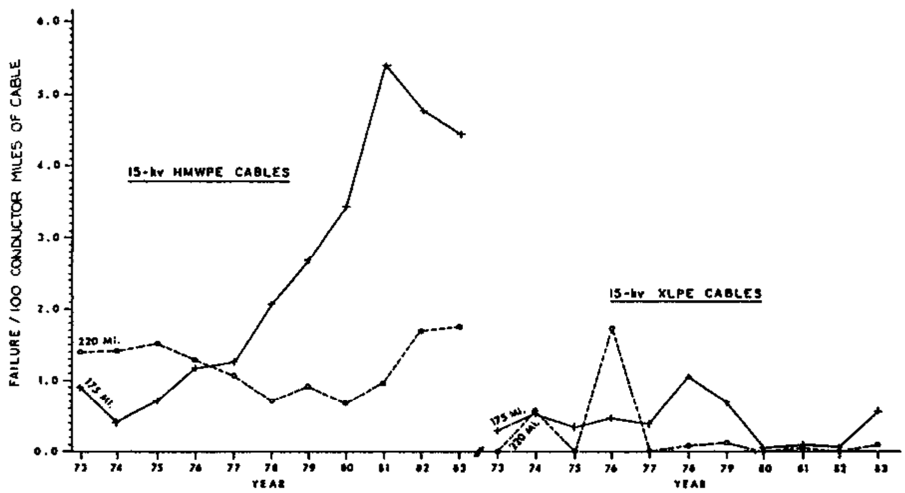


Fig. 1. Failure rates of 15-kV URD cables.

HMWPE cable seems to be failing at a much higher rate than XLPE cable. These failures seem to be related to treeing problems, which break down the insulation material. (See Fig. 1 for a plot of the data.)

Some member utilities have started to purchase tree-retardant insulation material. The usage has been limited and no failures have been reported.

In addition, 175-mil thickness insulation seems to have a much higher failure rate than 220-mil insulation. This is apparently due to the larger electrical stress capability of 220-mil insulation.

Secondary Cables

The failure rate for secondary low-voltage cables (600 V and below) has remained fairly constant for the last two years. The failure rates since 1969 are as follows.

1969	1.5	failures per 100 conductor miles
1970	1.25	failures per 100 conductor miles
1971	0.74	failures per 100 conductor miles
1972	0.62	failures per 100 conductor miles
1973	0.35	failures per 100 conductor miles
1974	0.50	failures per 100 conductor miles
1975	0.39	failures per 100 conductor miles
1976	0.53	failures per 100 conductor miles
1977	0.73	failures per 100 conductor miles
1978	0.71	failures per 100 conductor miles
1979	0.73	failures per 100 conductor miles
1980	0.48	failures per 100 conductor miles
1981	0.80	failures per 100 conductor miles
1982	0.70	failures per 100 conductor miles
1983	0.78	failures per 100 conductor miles

Failures of this cable seem to be related mostly to mechanical-type damage occurring during or after installation. Corrosion problems due to moisture do not seem to be a problem. (See Table IV for complete data.)

Plug-In Elbow Connectors

The failure rate for 15-kV, 25-kV, and 35-kV loadbreak elbows of 0.41 failures per 1000 units (unit defined as one

TABLE IIIA
PRIMARY CABLE—15 kV

	Type	Company	Miles* Installed	Failures This Year	Failures to Date	Average Life Before Failure	Neutral Corrosion
(A)	HMWPE 175 mil, 15 kV	A	18	0	23	Unknown	
		B	1170	34	118	7–8 yrs	
		C	1388	97	412		
		E	3161	86	545	13 yrs	8
		G	1085	83	529	12 yrs	10
	Total		6822	300	1627		
(B)	HMWPE 175 mil, 15 kV tree retardant	C	504	0	0		
		E	1106	0	0		
	Total		1610	0	0		
(C)	HMWPE 220 mil, 15 kV	A	1	0	0	12 yrs	
		C	74	16	86	Unknown	
		D	2373	31	255	Not reported	
		F	488	3	6	20 yrs	
	Total		2896	50	351		
(D)	HMW-Poly 220 mil, 15 kV tree retardent	D	60	0	0		
(E)	XLP 175 mil, 15 kV	A	1960	21	117	Unknown	
		B	150	0	0		
		C	615	0	0		
		E	1519	0	14		
		G	60	1	3		
	Total		4154	22	134		
(F)	XLP 175 mil, 15 kV tree retardant	E	318	0	0		
(G)	XLP 175 mil, 15 kV tree retardant with insulated jacket	E	90	0	0		
(H)	XLP 175 mil jacket, 15 kV	G	149	0	0		
	Total		149	0	0		
(I)	XLP 220 mil, 15 kV	C	1	0	0		
		D	2417	0	10	Not reported	
		F	†	†	†		
	Total		2418	0	10		
(J)	Butyl-neoprene, 15 kV	A	1	1	1		
		D	10	0	1		
		E	79	2	15	21 yrs	
	Total		90	3	17		
(K)	EPR 175 mil, 15 kV	A	3	0	4		
	GRAND TOTAL		18 610	375	2143		
	LAST YEAR'S GRAND TOTAL		17 751	376	1768		

* Conductor miles (*not* circuit miles).
† Accurate data not available.
(Data from NUDC Report No. 17, October 8, 1984.)

TABLE IIIB
PRIMARY CABLE—25 AND 35 kV

	Type	Company	Miles[a] Installed	Failures This Year	Failures to Date	Average Life Before Failure	Neutral Corrosion
(A)	HMWP 260 mil, 25 kV	G	125	0	8		
(B)	HMWP 260 mil, 25 kV	B	80	8	15	8–10 yrs	
(C)	HMWP 260 mil, 25 kV	C	930	75	432		
(D)	HMWP 295 mil, 25 kV	C	108	26	67		
(E)	HMWP 280 mil, 25 kV	A	2	0	55	11 yrs	
	Total		1245	109	577		
(F)	HMWP 260 mil, 25 kV tree retardant	C	348	0	0		
(G)	XLP 260 mil, 25 kV	B	11	0	0		
(H)	XLP 260 mil, 25 kV	C	409	0	4		
(I)	XLP 295 mil, 25 kV	F	[b]	[b]	[b]		
	Total		420	0	4		
(J)	XLP 260 mil, 25 kV with jacket	B	326	0	0		
(K)	EP 295 mil, 25 kV	A	5	0	2		
(L)	HMWP 345 mil, 35 kV	C	74	0	22		
(M)	HMWP 345 mil, 35 kV tree retardant	C	31	0	0		
(N)	HMWP 345 mil, 35 kV tree retardant	E	98	0	0		
	Total		129	0	0		
(O)	XLP 280 mil, 35 kV	A	10	0	2		
(P)	XLP 345 mil, 35 kV	A	102	1	2	2 yrs	
(Q)	XLP 345 mil, 35 kV	C	34	0	0		
(R)	XLPE 345 mil, 35 kV	E	29	0	0		
(S)	XLPE 345 mil, 35 kV	G	5	0	0		
	Total		180	1	4		
(T)	XLP 345 mil, 35 kV tree retardant	E	48	0	0		
(U)	XLP 345 mil, 35 kV tree retardant with insulated jacket	E	17	0	0		
GRAND TOTAL			2792	110	609		
LAST YEAR'S GRAND TOTAL			2251	127	498		

[a] Conductor miles (*not* circuit miles).
[b] Accurate data not available.
(Data is from NUDC Report No. 17, October 8, 1984).

TABLE IV
LOW-VOLTAGE CABLE

Type Insulation	Company	Thickness	Miles[a] Installed	Failures This Year	Failures to Date	Average Life Before Failure	Neutral Corrosion
(A) Poly	C		0	0	0		
	D	(Sodium)	12	0	4[c]	2 ½ yrs	
	E		0	0	0		
Total			12	0	4		
(B) XLPE	A	70–110 mil	2983	165	543	Unknown	
	B	70–110 mil	1300	1	21		
	C	60–110 mil	11 295	87	914	Unknown[b]	All neutral
	D	80–95 mil	8128	5	89		
	E	Min. IPCEA	5520	5	47	(Failures[b] starting with 1976 data)	
	G	60–110 mil	2096	Unknown	Unknown		
Total			31 322	263	1614		
(C) Abrasion-resistant XLPE	E		9	0	0		
	G		0.2	0	0		
Total			9.2	0	0		
(D) Abrasion-resistant HMWP	A		46	0	0		
	E		697	0	0		
Total			743	0	0		
(E) PVC	A	80 mil	10	0	1		
	C		0	0	0		
	D		7.1	0	0		
	E		0	0	0		
Total			17.1	0	1		
(F) Rubber neoprene	C		195	0	0		
	D	65 & 65 mil	1162	0	11		
	E	5/64 in	99	0	3		
Total			1456	0	14		
GRAND TOTAL			33 550.1	263	1633		
LAST YEAR'S GRAND TOTAL			31 978.9	225	1370		

[a] Insulated conductor miles (*not* circuit miles).
[b] Some of these failures could have been rubber neoprene, but no record is available as to which type cable failed. More failures are being reported due to a computer-managed reporting system.
[c] Cable insulation failed due to mechanical stress placed on it by the design of the connector. (A stainless-steel hose clamp around the insulation makes a quick fix.)
(Data is from NUDC Report No. 17, October 8, 1984.)

single-phase terminator) has been fairly constant over the last four years. Many of the recent problems were due either to molding problems of one manufacturer, cross-threading of connectors, or bad compression joints. These failures include units that were improperly installed, which is a significant number. The failures also include units that were replaced during maintenance due to problems such as visible tracking overheating, etc. (See Table V for complete data.)

Primary Connections

This is the fifth year for the study of primary cable splices and primary load break functions. Since the data is relatively new the results should be used carefully.

The failure rate for 15-kV splices was 2.1 failures per 1000 units (unit defined as one single-phase splice), compared to last year's 2.4 failures; the failure rate for 15-kV primary junctions was 1.0 failures per 1000 units, compared to last year's 1.3 failures. Splice failures over the last couple of years have been due mostly to the molding problems experienced by one manufacturer and to improper installation by line crews. (See Table VI for completed data.)

Pole Top Terminators

The outstanding performer for all voltage classes (15 kV, 25 kV, and 35 kV) is the molded rubber terminator. The failure rate is 0.06 per 1000 units (unit defined as one single-phase

TABLE V
PLUG IN PRIMARY TERMINATORS (ELBOWS)

	Type	Company	Total Number on System	Failures This Year	Failures to Date	Average Life Before Failure
(A)	Non-LB rubber, 15 kV	A	65	0	0	
		C	1628	0	3	
		D	2302	0	41	
		E	6440	0	51	
		G	200	0	0	Unknown
	Total		10 635	0	100	
(B)	Non-LP rubber, 600 A-15 kV	A	707	0	0	
		C	0	0	0	
		D	322	0	2	
		E	1972	0	9	
		G	25	0	0	
	Total		3026	0	11	
(C)	Non-LB rubber, 600 A-25 kV	C	33	0	0	
		E	0	0	0	
		F	*	*	*	
	Total		33	0	0	
(D)	Non-LB rubber, 600 A-35 kV	E	30	0	0	
	Total		30	0	0	
(E)	Non-LB metal	A	40	0	0	
		C	15	0	1	
	Total		55	0	1	
(F)	LP rubber 15 kV	A	31 138	18	168	
		B	21 514	32	71	
		C	40 997	27	231	
		D	76 525	21	180	
		E	160 506	44	370	
		F	*	*	*	
		G	24 179	2	15	
	Total		354 859	144	1035	
(G)	LB rubber, 25 kV	B	797	4	19	
		C	24 311	5	27	
		E	0	0	0	
		F	*	*	*	
		G	565	0	4	
	Total		25 673	9	50	
(H)	LB rubber, 35 kV	A	2465	0	2	1 yr
		C	2293	5	19	
		E	730	0	0	
	Total		5488	5	21	
GRAND TOTAL			399 799	158	1218	
LAST YEAR'S GRAND TOTAL			371 119	160	1060	

* Accurate data not available.
(Data is from NUDC Report No. 17, October 8, 1984.)

TABLE VI
PRIMARY CONNECTIONS

Type	Company	Total Number on System	Failures This Year	Failures to Date	Average Life Before Failure
Primary splices—15 kV, molded rubber	A	13 454	48	443	10 yrs
	B	7484	68	149	
	C	17 624	6	15	
	D	21 481	4	35	
	E	18 990	65	389	
	G	11 813	3	25	
Total		90 846	194	1056	
Primary splices—25 kV, molded rubber	B	309	3	5	
	C	11 332	1	3	
	G	520	0	4	
Total		12 161	4	12	
Primary splices—35 kV, molded rubber	A	711	1	6	
	C	1057	0	16	
	E	437	0	0	
	G	32	0	0	
Total		2237	1	22	
GRAND TOTAL		105 244	199	1090	
LAST YEAR'S GRAND TOTAL		94 281	203	891	
Primary loadbreak junctions (lateral taps)—15 kV	A	3474	13	138	4–8 years
	B	3224	18	30	
	C	7321	3	9	
	D	8742	4	31	
	E	30 555	19	213	
	G	2103	0	2	
Total		55 419	57	423	
Primary loadbreak junctions (lateral taps)—25 kV	B	42	1	4	
	C	3587	3	7	
	G	16	0	0	
Total		3645	4	11	
Primary loadbreak junctions (lateral taps)—35 kV	C	306	1	2	
	E	261	0	0	
Total		567	1	2	
GRAND TOTAL		59 631	62	436	
LAST YEAR'S GRAND TOTAL		55 195	71	374	

Note: Data on taped primary splices has been discontinued due to lack of data.
(Data from NUDC Report No. 17, October 8, 1984.)

terminator). The porcelain elastomeric type has a rate of 0.43 per 1000 units. Overall the record for these devices is excellent. (See Table VII for complete data.)

SECONDARY CONNECTIONS

This is the sixth year of evaluating the different types of secondary connections 600 V and below made by the member utilities. This data should be used carefully due to the difficulty in tabulating failures from previous years. The section on taped-insulated connections has been discontinued since the data is not dependable. Even though the data is new, the numbers on heat-shrink connections appear to be particularly interesting due to the failure rate of 0.002 per 1000 units (unit defined as one single-phase connection) for 1983 on 513 280 units installed. This compares with the failure rate of 0.00 per 1000 units for 1982. The failure rate for the molded

TABLE VII
POLE TOP TERMINATORS

	Type	Company	Total Number on System	Failures This Year	Failures to Date	Average Life Before Failure
(A)	Porcelain compound	A	192	0	7	8 yrs
		C	125	0	3	
		D	115	0	0	
		E	75	0	3	17 months
	Total		507	0	13	
(B)	Porcelain epoxy	E	125	0	3	
(C)	Porcelain elastomer—15 kV	B	Unknown	1	10	
		C	1631	2	20	
		D	2732	0	2	
		E	25 522	11	230	Unknown
	Total		37 126	16	271	
(D)	Porcelain elastomer—25 kV	C	1320	2	12	
	Total		1320	2	12	
(E)	Porcelain elastomer—35 kV	A	137	0	0	
		E	448	0	0	
	Total		585	0	0	
(F)	Porcelain elastomeric compound 35 kV	C	18	0	1	
		A	37	0	0	
	Total		55	0	1	
(G)	Molded rubber—15 kV	A	1840	0	1	
		B	14 359	2	15	
		C	17 861	2	34	Unknown
		D	32 576	2	8	2 yrs
		F	*	*	*	
		G	10 045	0	12	
	Total		76 681	6	70	
(H)	Molded rubber—25 kV	B	600	0	0	
		C	12 064	0	7	
		F	*	*	*	
		G	369	0	2	
	Total		13 033	0	9	
(I)	Molded rubber—35 kV	A	1071	0	0	
		C	972	0	4	
		G	40	0	0	
			*	*	*	
	Total		2083	0	4	
(J)	Taped	A	7*	0	1	
		C	0	0	0	
		D	200	0	21	
	Total		229	0	22	
(K)	Scotch 83A3	A	227	0	23	
		F				
	Total		227	0	23	
(L)	Heat shrink—15 kV	E	9397	0	4	
		C	7	0	0	
	Total		9404	0	4	

TABLE VII
(Continued)

	Type	Company	Total Number on System	Failures This Year	Failures to Date	Average Life Before Failure
(M)	Heat shrink—25 kV	C	80	0	1	
	Total		80	0	1	
(N)	Heat shrink—35 kV	E	363	0	0	
		C	21	1	3	
	Total		384	1	3	
GRAND TOTAL			141 839	25	436	
LAST YEAR'S GRAND TOTAL			133 271	21	411	

* Accurate data not available.
(Data from NUDC Report No. 17, October 8, 1984.)

TABLE VIII
SECONDARY CONNECTIONS

	Type	Company	Total Number on System	Failures This Year	Failures to Date	Average Life Before Failure
(A)	Molded rubber/ plastic insulated connections	A	53 162	5	36	
		B	—	—	—	
		C	1093	0	2	
		D	292 399	6	242	
		E	155 284	2	171	
		F	*	*	*	
		G	44 245	0	10	
	Total		546 183	13	461	
(B)	Heat shrink connections	A	47 987	1	11	1 yr
		B	—	—	—	
		C	147 184	Unknown	Unknown	
		D	53 100	0	1	
		E	265 009	0	6	
		F	*	*	*	
	Total		513 280	1	18	
GRAND TOTAL			1 059 463	14	479	
LAST YEAR'S GRAND TOTAL			965 121	13	465	

* Accurate data not available.
(Data from NUDC Report No. 17, October 8, 1984.)

rubber-plastic units is 0.02 failures per 1000 units for 1983, which is the same as for 1982. (See Table VIII for data.)

References

[1] Northwest Underground Distribution Committee of the Northwest Electric Light and Power Association (NELPA), "URD equipment and materials reliability in the Northwest," no. 17, October 8, 1984.

[2] IEEE Committee Report, "Report on reliability survey of industrial plants," published in six parts, *IEEE Trans. Ind. Appl.*, pp. 213-252, 456-476, 681, Mar./Apr., July/Aug., Sept./Oct. 1974. (Included as Appendices in [3].)

[3] ANSI/IEEE Standard No. 493-1980, "IEEE Recommended Practice for the Design of Reliable Industrial & Commercial Power Systems."

William F. Braun (M'76) received the B.S.E.E. degree from the University of Toledo in 1970.

He worked at the Ohio Power Company, Newark, OH, as an Engineer in the Transmission and Distribution Department from 1971 to 1973. Since 1973 he has been employed at the Owens-Corning Fiberglas Corporation, Toledo, OH. Presently he is working as a Senior Electrical Engineer in the Power Systems Section of Corporate Electrical Engineering of Owens-Corning.

Mr. Braun is a member of IEEE/IAS Power Systems Reliability Subcommittee.

Summary of CIGRE 13.06 Working Group World Wide Reliability and Maintenance Cost Data on High Voltage Circuit Breakers above 63 kV

By
C. R. Heising, A. L. J. Janssen, W. Lanz,
E. Colombo, E. N. Dialynas

IEEE-IAS Industrial Application Conference
Denver, Colorado
October 2–5, 1994

Reprint from IEEE Conference Record
94CH34520, pp. 2226–2234

SUMMARY OF CIGRE 13.06 WORKING GROUP WORLD WIDE RELIABILITY DATA AND MAINTENANCE COST DATA ON HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 kV

C. R. Heising
U. S. A.

A. L. J. Janssen
Netherlands

W. Lanz
Switzerland

E. Colombo
Italy

E. N. Dialynas
Greece

ABSTRACT

A summary is given of the most significant reliability data and maintenance cost data from the two CIGRE 13.06 Working Group world wide reliability surveys of the reliability of high voltage circuit breakers 63 kV and above. The first enquiry covered the years 1974 thru 1977 and included all interrupting technologies. The second enquiry covered the years 1988 thru 1991 and only included single pressure SF6 breakers.

A description is given of the scope and objectives of the CIGRE 13.06 Working Group. A brief description is given of some of the highlights from their studies.

INTRODUCTION

CIGRE 13.06 Working Group carried world wide reliability studies on high voltage circuit breakers during the fifteen year period 1971 through 1985. This included making the First International Enquiry on circuit breaker failures and defects in service. Studies were also made on new testing and maintenance methods for improving the reliability of high voltage circuit breakers. This work is reported in three CIGRE Study Committee No. 13 final reports [1] [2] [3]. Some of the CIGRE 13.06 WG recommendations have resulted in changes in International Standards for high voltage circuit breakers.

SCOPE AND OBJECTIVES OF NEW CIGRE 13.06 WG

In 1986 a new CIGRE 13.06 Working Group was set up on "Reliability of High Voltage Circuit Breakers" in order to obtain detailed information on circuit breaker performance in service as well as possible measures to improve the reliability and to reduce the maintenance costs. Two major tasks were undertaken:

1. Conduct a Second International Enquiry on the in service reliability of SF6 single pressure high-voltage circuit breakers with rated voltages 72.5 kV and above.

2. Study the parameters for permanent supervision in service as well as relevant diagnostic methods.

The results of the Second International Enquiry on circuit breaker failures and defects in service show the change in reliability since the First Enquiry. Monitoring and diagnostic methods aim to improve the reliability of operation and contribute to reducing the cost of maintenance. Studies on monitoring and diagnostic methods include all circuit breaker technologies because there is interest for both new and older circuit breakers.

Four papers have been published during 1992 to 1994 on the results of these studies [4] [5] [6] [7]. In addition, a Technical Brochure has been published [8] that gives extensive details on the reliability of high voltage circuit breakers above 63 kV and the changes in reliability that have occured during the fourteen year interval between the First and Second International Enquiries.

CIRCUIT BREAKER RELIABILITY DEFINITIONS USED IN TWO INTERNATIONAL ENQUIRIES

The CIGRE 13.06 WG wrote circuit breaker reliability definitions in 1971 for "failure," "major failure," "minor failure," and "defect." These definitions were used in both the First and Second International Enquiries and are given in Table 1. Thus world wide reliability definitions have existed for several years for high voltage circuit breakers and are now included in technical report IEC 1208 (1992) "Guide for High-Voltage Alternating Current Circuit Breaker Maintenance" by TC17 on Switchgear and Controlgear. It can be seen that the term "circuit breaker major failure" is equivalent to what system planning people would call a "forced outage."

The term "circuit breaker downtime" was clearly defined in the Second International Enquiry as "time from discovery of the failure until the breaker is returned to service, exclude deliberate delays." In the First International Enquiry "circuit breaker downtime" was calculated by adding two terms: (1) "time required to analyse the failure or defect, repair and return the circuit breaker to service, exlude deliberate delays," plus (2) "time required to get to site and obtain spare parts, exclude deliberate delays." This change in definition of "circuit breaker downtime" was made in the Second Enquiry because it was believed that some respondents in the First Enquiry may have misinterpreted what was asked for. However, it should be noted that deliberate delays for repair of the circuit breaker have been excluded in both enquiries when calculating "circuit breaker downtime."

RELIABILITY DATA FROM FIRST ENQUIRY

A total of 102 electric utilities from 22 countries submitted data on 20,000 circuit breakers above 63 kV. This included breakers

0-7803-1993-1/94 $4.00 © 1994 IEEE

of all technologies. Data were collected for the years 1974-77 on circuit breakers installed after January 1, 1964. This gave a total of 77,892 breakers-years of service during the four year period. This was a pioneering effort that required the development of: (1) reliability and maintenance definitions , (2) survey questionaire, and (3) the method of analysis of the data. This encouraged utilities to develop a failure reporting system. Countries submitting data were: Australia, Belgium, Brazil, Canada, Czechoslovakia, Denmark, Finland, France, Federal Republic ofGermany, Greece, Ireland, Italy, Japan, Morocco, Netherlands, New Zealand, Norway, Portugal,Spain, Sweden, United Kingdom, and Yugoslavia. The results from this First InternationalEnquiry were published in "Electra" [1].

The failure rate and downtime data are summarized in Table 2 with the data for major failure rate and minor failure rate shown separately. Average downtime data and the median downtime data are given for major failures.

RELIABILITY DATA FROM SECOND ENQUIRY

The enquiry includes the years 1988 thru 1991 and was limited to single pressure SF6 circuit breakers because most of the new breakers at these voltage levels now being purchased by electric utilities use this technology. The questionaire [8][9] was revised to be simpler than for the First Enquiry.

Data were collected for 1988 thru 1991 from 132 utilities in 22 countries on about 18,000 circuit breakers applied at 63 kV & above placed in service after January 1, 1978. There were a total of 70,708 breaker-years of service during the four year period. Countries submitting data were: Australia, Austria, Belgium, Brazil, Canada, Czechoslovakia, Finland, France,Germany, Italy, Japan, Netherlands, New Zealand, Norway, Paraguay, Rumania, Sweden, Switzerland, United Kingdom, United States of America, Union of Soviet Socialist Republics, and Yugoslavia.

Table 3 shows the major and minor failure rates separately. Average downtime data and median downtime data are given for major failures.

The questionaire for the Second Enquiry contains the additional major failure mode "locking in open or closed position." A study of this "locking" data indicates that about 13% were found during a command to open, about 37% were found during a command to close, and 50% were found by an alarm during normal service.

ORIGIN,CAUSE, FAILURE MODES, OPERATING-CYCLES

Tables 4 and 5 show the major and minor failure modes for the two enquiries. Table 6 shows the origins of failures, and Table 7 shows the causes of failures.

Table 8 shows the estimated average number of operating-cycles per year per breaker from the two enquiries.

DATA FOR USE IN SUBSTATION AND SYSTEM RELIABILITY STUDIES

Data from Tables 2 and 3 from the First and Second Enquiries have been used respectively to calculate the data shown in Tables 9 and 10. In both cases the major failures that occured during a command to open or close have been separated out from those that occurred without a command to open or close; this has been used along with the operating-cycles per year data to calculate the reliability data that is given in Tables 9 and 10. This shows the average number of major failures per 10,000 open commands or close commands of: "does not open on command", "does not break the current", "does not close on command", "does not make the current." These final results in Table 10 from the Second Enquiry can be compared with Table 9 from the First Enquiry. A footnote in each table gives the data for the two failure modes: "closes without command" and "breakdown across open pole;" these failure rates are very low, but may have a serious consequence when they occur on a power system.

COMPARISON OF RELIABILITY DATA BETWEEN THE FIRST AND SECOND ENQUIRIES

The final results from the Second International Enquiry for 1988 thru 1991 show that modern single-pressure SF6 circuit breakers applied at 63 kV & above have a major failure rate that is only 43% as much as older technology circuit breakers reported in the First International Enquiry for 1974-1977. The largest improvement has occurred at voltages above 200kV where the reported major failure rates are less than one-third as much. The minor failure rates are 30% higher in the Second Enquiry.

It is believed that utilities do a better job of collecting failure data now than was done during the First Enquiry. The biggest improvement is believed to have occurred in the collection of data on minor failures.

The "estimated average number of operating-cycles per year per breaker" were 42 and 26.5 respectively from the Second and First International Enquiries. These values have an effect on the calculated probabilities of breaker major failures per operating command. The Second Enquiry calculated the average number of operating-cycles per year per breaker by weighting each breaker equally. This is a better method than used in the First Enquiry where each questionaire answer was weighted equally, and some answers contained many more breakers than other answers. It is not believed that there has been a significant change in the number of operating-cycles per year per breaker between the First and Second Enquiries. If 42 operating-cycles per year per breaker had been used to calculate the probabilities of breaker major failures per operating command for the First Enquiry, the probabilities shown in Table 9 would have been lower by a factor of 1.58.

Tables 10 and 9 can be compared to show the number of major failures per 10,000 cycles, where a cycle is one open command plus one close command. For all voltages combined the

Second Enquiry shows 0.829 versus 3.06 for the First Enquiry and is a factor of 3.7 lower. But 1.58 of this improvement is explained in the previous paragraph because of using an estimated average of 42 operating-cycles per year per breaker versus 26.5 from the First Enquiry; and 3.7 divided by 1.58 equals 2.33. Thus the number of major failures per 10,000 cycles has decreased by at least a factor of 2.33.

COMPARISON OF BREAKER DOWNTIME DATA PER MAJOR FAILURE BETWEEN THE FIRST & SECOND ENQUIRIES

The Second Enquiry had an average downtime of 94.6 hours per major failure versus 81.6 in the First Enquiry. But the median downtime was only 10.0 hours hours in the Second Enquiry versus 12.0 in the First Enquiry. Both enquiries show a highly skewed distribution where a small number of long downtimes result in the average being between about seven to nine times larger than the median value. Some people have questioned why the Second Enquiry had a longer downtime than the First Enquiry. A special detailed study has been made of the downtime data from the Second Enquiry. The increase in breaker downtime for SF6 single pressure breakers is primarily due to a much longer "time to obtain spare part." 64% of the 94.6 hours per failure of average breaker downtime for "all voltages combined" can be attributed to "time to obtain spare part." This would appear to be due to the policies of electric utilities on spare parts rather than the ability to repair the breaker. In 9% of the reported cases the "time to obtain spare part" was longer than the breaker downtime; this would indicate that the breaker was often placed back in service or was replaced before the spare part was obtained. The special study also found that there does not appear to be any significant difference in the breaker downtime between metal-enclosed and non-metal-enclosed SF6 breakers.

Data were not collected in the Second Enquiry on the breaker downtime for minor failures. This data were collected in the First Enquiry; and the average was 30.0 hours per minor failure with a median of 6.0.

SUBSTATION AND SYSTEM RELIABILITY STUDIES

The data in Tables 9 and 10 are a credible source of data based upon a large sample size. They can be used in substation and system reliability studies. Very few reliability studies use all of the breaker failure modes given in this data. The circuit breaker is the most difficult component to handle when making substation or system reliability studies because of the many different breaker functions and the associated failure modes.

λ_s is the major failure rate without a command to operate. 63% of these failures for all voltages combined include the failure modes: alarm-locking in open or closed position, fails to carry the current, other requiring manual removal from service within 30 minutes. These might be assumed to be passive failures. The other 37% might be assumed to be active major failures (breakdown to earth, breakdown between poles, breakdown across open pole, closes without command, opens without command).

$c \cdot \lambda_c$ is the major failure rate during commands to operate, either for switching or to remove faults.

$\lambda_{c1} + \lambda_{c2}$ is the probability of not opening on command or not breaking the current during manual or automatic opening to perform switching or to remove a fault. This could be considered the breaker stuck closed probability.

$\lambda_{c3} + \lambda_{c4}$ is the probability of not closing on command or not making the current during manual or automatic closing or reclosing. This could be considered the breaker stuck open probability.

The dominant breaker failure mode is "does not close on command" and should not be neglected in substation or system reliability studies. This failure mode: (1) can prevent equipment from being switched into service when needed, (2) can cause a transient line outage to become a permanent outage, or (3) can cause an outage of a line or generator to be extended beyond the normal outage time.

The failure mode "closes without command" has a very low failure rate. But its occurence sometimes results in all of the back up protection being defeated and in some cases has been the cause of major blackouts. The failure mode "breakdown across pole" has the highest electrical failure rate of the main interrupter; and backup protection must operate to remove the fault. The failure rates of "closes without command" and "breakdown across open pole" are both very low; but they can be larger than the double contingency failure rates typically calculated for other component combinations in a substation reliability study.

COST OF SCHEDULED SERVICING OF OLDER TECHNOLOGY BREAKERS

Table 11 shows the cost of scheduled servicing of older technology breakers (minimum oil, air blast, SF6, bulk oil, etc) that was collected from the First International Enquiry [1] for the years 1974-1977. The costs are shown separately for the labor effort and for the spare parts consumed. The 10, 50, and 90 percentiles cost values are given along with the average cost value for each voltage category. The number of data points in each voltage category ranged from 69 to 138. It can be seen that there is a wide variation between the 10 and 90 percentiles cost values for the labor effort, typically as much as six to one or more. There is even a wider variation in the costs of the spare parts consumed. These cost values indicate that many users of high voltage circuit breakers may be doing more scheduled maintenance than needed. In some cases it might be possible to reduce the maintenance effort without the use of additional diagnostic techniques. In other cases it might be desirable to use additional diagnostic techniques in order to detect degradation of the most probable failure modes before they occur in service[4][5]. Table 11 gives data that can be used to assist in estimating the maximum cost savings that might be possible from using diagnostic techniques on older technology circuit breakers.

COST OF SCHEDULED OVERHAUL OF MODERN TECHNOLOGY BREAKERS

Table 12 shows the estimated cost of scheduled overhaul for single pressure SF6 breakers that has been collected during the four years (1988-1991) of the Second International Enquiry. The costs are shown separately for the labor effort and for the spare parts consumed for each voltage category along with the 10, 50, 90 percentile and average values. The number of data points in each voltage category ranged from 179 to 601. The data on the interval betweeen scheduled overhaul show that the 50 percentile value ranged from 6. to 8.5 years for the various voltage categories, but the 90 percentile value ranged from 12.0 to 15.0 years for all voltage categories. Most manufacturer's quote longer overhaul intervals than 8. years, and many utilities may not yet have sufficient confidence to fully exploit the longer overhaul interval possible with modern technology single pressure SF6 breakers. The variation in the labor costs ranged by a factor of six to one or more, and the spare parts consumed ranged by a factor or more than twenty to one; many of these utility estimates maybe based upon very limited experience with overhaul of single pressure SF6 breakers.

TIGHTNESS OF SF6 GAS SYSTEM

Table 6 shows that the tightness of the SF6 gas system was the origin of both minor and major failures in the Second Enquiry on SF6 single-pressure breakers. This included 39.6% of the minor failures and 7.2% of the major failures. The data in Table 5 show that 1297 minor failures were due to small SF6 leakage, and this was 39% of all minor failures. The minor failure rate for these 1297 failures is .018 per year per breaker.

There was a total of 33 major failures with the origin in the tightness of the SF6 gas system, and Table 13 shows the failure modes that resulted. 18 resulted in "locking in open or closed position" and 5 resulted in "opens without command." The major failure rate for these 33 failures is .00025 per year per breaker and is very low.

A density monitor is used to detect SF6 gas leaks, and this is the primary resson why most of the tightness failures are minor failures. However, 357 failures have also been reported of the density monitor.

Reliability improvements are needed in both the SF6 gas tightness system and in the gas density monitor.

FAILURE RATE OF METAL-ENCLOSED VERSUS NON-METAL ENCLOSED CIRCUIT BREAKERS

Table 13 shows a comparison of the failure rates from the Second Enquiry of metal-enclosed (ME) versus non-metal-enclosed circuit (NME) breakers for "all voltages combined, 100 kV and above." Most of the ME breakers are part of gas insulated stations.

The ME SF6 single-pressure breakers, 100 kV & above, have a lower failure rate than the NME breakers. But this difference can not be considered significant because it is mostly due to data from one country with a large population.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

CIGRE 13.06 Working Group has collected and analysed world wide reliability data on high voltage circuit breakers applied on networks at 63 kV & above. These data are a large sample size and can be useful in substation and system reliability studies. Two important contributions to the knowledge of circuit breaker reliability are: (1) the failure mode data, and (2) the calculations of probabilities of not responding properly to an operating command to open or to close. The 1974-1977 data can be used for older technology circuit breakers, and the 1988-1991 data show the improvement that has been achieved with new technology single-pressure SF6 breakers. The major failure rate for modern SF6 single-pressure breakers is only about 43%as much as older technology breakers, and for voltages above 200 kV it is only one-third as much. Substation and system reliability studies should pay attention to this improvement. The lower major failure rate of circuit breakers may influence both the lay-out of primary plant and secondary systems.

The minor failure rate for modern SF6 breakers in the Second Enquiry is about 30% higher than for older technology breakers in the First Enquiry. Possible reasons for this may be: (1) better failure data collection by utilities and (2) increased number of alarms and (3) SF6 leakage problems.

The largest number of major failures on modern SF6 breakers occur on the operating mechanism and on the electrical auxiliary and control circuits. The largest number of minor failures occur from leaks on the SF6 gas system and from problems on the operating mechanism. Reliability improvements are needed on: (1) operating mechanism, (2) SF6 tightness, (3) electrical auxiliary & control circuits. The gas density monitor also needs improvement in reliability because the SF6 gas density is the most important parameter to monitor. The operating mechanism is also an important parameter to monitor.

Design and manufacture are the cause of about 50% of the failures of modern SF6 breakers.

Improved access to spare parts by utilities could significantly improve breaker availability by reducing the downtime after major failures.

The circuit breaker reliability definitions that were first written in 1971 are now accepted and used world wide. Thus it logical that these definitions become standards of the International Electrotechnical Comission (IEC) under Technical Committee No. 17 on Switchgear and Controlgear. It is recommened that the existing technical report IEC 1208 (1992) on "Guide for High-Voltage AC Circuit Breaker Maintenance" be upgraded to an IEC standard after the three trial period is completed.

TABLE 1 - CIRCUIT BREAKER RELIABILITY DEFINITIONS

1. FAILURE - Lack of performance by an item of its required functions.
Note: The occurenceofa failuredoes not necessarily imply the presence of a defect if the stress or the stresses are beyond those specified.

2. MAJOR FAILURE (OF A CIRCUIT-BREAKER) - Complete failure of a circuit-breaker which causes the lack of one or more of its fundamental functions.
Note: A majorfailure will result in an immediate change in the system operating condition; e. g., the backup protective equipment being required to remove the fault, or, will result in mandatory removal from service for non scheduled maintenance (intervention required within 30 minutes).

3. MINOR FAILURE (OF A CIRCUIT-BREAKER) - Failure of circuit-breaker other than major failure; or any failure, even complete, of a constructional element or a sub-assembly which does not cause a major failure of the circuit-breaker.

4. DEFECT - Imperfection in the state of an item (or inherent weakness) which can result in one or more failures of the item itself or of another item under the specific service or environmental or maintenance conditions for a stated period of time.

5. CIRCUIT-BREAKER DOWNTIME - Time from the discovery of the failure until the breaker is returned to service.

TABLE 2 - FAILURE RATES AND DOWNTIME DATA FOR HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 kV (from CIGRE 13-06 Working Group First International Enquiry, 1974-1977, All Interrupting Technologies)

MAJOR FAILURE RATES						*MINOR FAILURE RATES		
Sample Size Breaker Years	Number of Major Failures	Major Failures per Breaker Year	*** Hours Downtime per Failure Average	Median	VOLTAGE kV	Sample Size Breaker Years	Number of Failures*	Failures* per Breaker Year
77,892	1,231**	.0158	81.6	12.0	All Voltages	46,272	1,641	.0355
33,877	138	.0041	29.3	5.0	63 ≤ V <100	24,716	409	.0165
26,743	437	.0163	94.4	12.0	100 ≤ V <200	13,915	581	.0417
9,939	257	.0258	58.5	11.0	200 ≤ V <300	5,614	359	.0639
6,224	283	.0455	83.8	11.0	300 ≤ V <500	1,682	275	.1635
1,109	116	.1045	142.0	27.0	500 ≤ V	345	17	.0493

NOTES: * Minor failures plus defects
** 45 of the 1,231 major failures had a fire and/or explosion
*** Downtime includes: time required to get to site, analyse the failure, obtain spare parts, repair and return circuit breaker to service. Deliberate delays have been excluded.

TABLE 3 - FAILURE RATES AND DOWNTIME DATA FOR SINGLE-PRESSURE HIGH-VOLTAGE CIRCUIT BREAKERS APPLIED ABOVE 63 kV (Final Results from CIGRE 13-06 Working Group Second International Enquiry, 1988-1991)

MAJOR FAILURE RATES						*MINOR FAILURE RATES	
Number of Major Failures	Major Failures per Breaker Year	*** Hours Downtime per Failure Average	Median	VOLTAGE kV	Sample Size Breaker Years	Number of Failures*	Failures* per Breaker Year
475**	.00672	94.6	10.0	All Voltages	70,708	3,358	.0475
67	.00275	39.1	24.0	63 ≤ V <100	24,355	542	.0223
160	.00680	51.1	10.0	100 ≤ V <200	23,520	1,118	.0475
89	.00814	54.6	8.0	200 ≤ V <300	10,933	762	.0697
120	.01210	162.5	10.0	300 ≤ V <500	9,917	770	.0776
39	.01967	209.4	36.0	500 ≤ V	1,983	166	.0837

NOTES: * Minor failures plus defects
** 31 of the 475 major failures had a fire and/or explosion
*** Downtime includes: time from discovery of the failure until the breaker is returned to service, exclude deliberate delays.

TABLE 4 - MAJOR FAILURE MODES OF HIGH VOLTAGE CIRCUIT BREAKERS (Results from CIGRE 13-06 WG Enquiries - All voltages, Above 63 kV)

1st Enquiry	2nd Enquiry	
%	%	
33.7	24.6	Does not close on command
14.1	8.3	Does not open on command
1.7	1.0	Closes without command
5.2	7.0	Opens without command
1.6	1.7	Does not make the current
1.9	3.0	Does not break the current
2.5	1.5	Fails to carry the current
2.6	3.2	Breakdown to earth
0.5	1.5	Breakdown between poles
4.0	3.6	Breakdown across open pole, internal
1.2	1.5	Breakdown across open pole, external
*	28.5	Locking in open or closed position
31.0	14.6	Other failure necessitating intervention within 30 minutes
773	471	Number of Answers

* "Locking" failure mode data not collected in 1st Enquiry. Special study of 2nd Enquiry data found that half of "Locking" failures should probably have been reported as "does not close on command" (37%) or "does not open on command" (13%).

TABLE 5 - MINOR FAILURE MODES* OF HIGH VOLTAGE CIRCUIT BREAKERS (Results from CIGRE 13-06 WG Second Enquiry - All Voltages, Above 63 kV)

%	
30.	Air or hydraulic leakage in operating mechanism
16.	Small SF6 gas leakage due to corrosion
23.	Small SF6 gas leakage due to other causes
16.	Change of functional characteristics
15.	Others
3332	Number of Answers

* Data not collected in First Enquiry

TABLE 6 - ORIGIN OF FAILURES OF HIGH VOLTAGE CIRCUIT BREAKERS (Results from CIGRE 13-06 WG Enquiries - All Voltages, Above 63 kV)

Major Failures 1st Enquiry	Major Failures 2nd Enquiry		Minor Failures 1st Enquiry	Minor Failures 2nd Enquiry
*	44.0%	Mechanical in Operating Mechanism (Earthed)	*	39.4%
70.3%	10.4%	Mechanical in Other Parts of Circuit Breaker	85.6%	9.9%
10.6%	13.9%	Electrical (Main circuit	2.7%	0.9%
19.1%	24.5%	Electrical Auxiliary and Control Circuit	11.7%	10.2%
*	7.2%	Tightness of SF6-Gas System	*	39.6%
775	461	Number of Failures	1602	3233

* Not specified in First Enquiry

TABLE 7 - CAUSE OF MAJOR AND MINOR FAILURES OF HIGH VOLTAGE CIRCUIT BREAKERS (Results from CIGRE 13-06 WG Enquiries - All Voltages, Above 63 kV)

Major Failures 1st Enquiry	Major Failures 2nd Enquiry		Minor Failures 1st Enquiry	Minor Failures 2nd Enquiry
	25.4%	Design		24.7%
*45.3%		Design & Manufacture	*52.5%	
	28.7%	Manufacture		39.1%
0.7%	1.1%	Inadequate Instructions	0.3%	1.7%
9.3%	8.2%	Incorrect Erection	10.7%	7.1%
1.2%	6.0%	Incorrect Operation	0.2%	4.5%
8.1%	2.8%	Incorrect Maintenance	4.5%	2.6%
4.8%	3.4%	Stresses Beyond Specification	0.7%	1.8%
2.3%	5.4%	Other External Causes	1.7%	6.6%
28.3%	19.0%	Other	29.4%	11.9%
751	464	Number of Failures	1604	3294

* First Enquiry combined "Design" and "Manufacture"

TABLE 8 - ESTIMATED AVERAGE NUMBER OF OPERATING-CYCLES PER YEAR PER BREAKER (Results from CIGRE 13-06 WG Enquiries - All voltages, Above 63 kV)

	1st Enquiry	2nd Enquiry
AVERAGE	26.5	42
10% PERCENTILE	3.3	13
25% PERCENTILE	6.3	20
MEDIAN	13.1	30
75% PERCENTILE	28.8	50
90% PERCENTILE	53.1	76
95% PERCENTILE	78.0	84
MAXIMUM	548.6	1760
No. of Breakers		*64,676
No. of Answers	*422	

* First Enquiry weighted each answer equally and Second enquiry weighted each breaker equally

TABLE 9 - RELIABILITY DATA ON HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 kV THAT CAN BE USED IN SYSTEM RELIABILITY STUDIES (from CIGRE 13-06 Working Group First International Enquiry 1974-1977, All Interrupting Technologies)

1. Major Failures per Open Command $\lambda_{c1} + \lambda_{c2}$
2. Major Failures per Close Command $\lambda_{c3} + \lambda_{c4}$
3. Major Failures per Cycle** $\lambda_c = \lambda_{c1} + \lambda_{c2} + \lambda_{c3} + \lambda_{c4}$
4. Average Number of Cycles** per Year C
5. Major Failures per Breaker-Year During Commands to Open or Close $C \cdot \lambda_c$
6. Major Failures per Breaker-Year Occuring Without A Command to Open or Close λ_s
7. Total Major Failures per Breaker-Year $\lambda_M = \lambda_s + C \cdot \lambda_c$

λ_{c1} Does Not Open On Command	λ_{c2} Does Not Break the Current	λ_{c3} Does Not Close On Command	λ_{c4} Does Not Make the Current	λ_c Major Failures per10,000 Cycles**	C Average Number of Cycles** per Year	VOLTAGE kV	$C \cdot \lambda_c$ Major Failure per Breaker Year	λ_s Major Failure per Breaker Year	λ_M Total Major Failure per Breaker Year
MAJOR FAILURES PER 10,000 OPEN COMMANDS		MAJOR FAILURES PER 10,000 CLOSE COMMANDS							
0.84	0.11	2.01	0.10	3.06	26.5	All Volt.	.0081	.0077***	.0158
0.166	0.018*	0.562	0.010*	0.756	24.7	$63 \leq V < 100$	.0019	.0022	.0041
0.81	0.12*	2.60	0.05*	3.58	23.8	$100 \leq V < 200$	.0085	.0078	.0163
1.42	0.07*	2.54	0.32*	4.35	32.0	$200 \leq V < 300$	.0139	.0119	.0258
3.16	0.64*	5.39	0.24*	9.43	25.0	$300 \leq V < 500$	.0236	.0219	.0455
9.75*	0.00*	12.98*	0.00*	22.73*	26.8	$500 \leq V$	.0609	.0436	.1045

NOTES
* Small sample size in failure mode data - less than 8 failures
** A cycle is one open command and one close command
*** Approximately 10.7% of these major failures are "breakdown across open pole" and another 3.5% are "closes without command"

TABLE 10 - RELIABILITY DATA ON SINGLE-PRESSURE HIGH VOLTAGE CIRCUIT BREAKERS APPLIED ABOVE 63 kV THAT CAN BE USED IN SYSTEM RELIABILITY STUDIES (from CIGRE 13-06 Working Group Second International Enquiry 1988-1991)

Assumes that 13% of the "Locking" Failures Occured After a Command to Open and Another 37% of the "Locking" Failures Occured After a Command to Close

λ_{c1} Does Not Open On Command	λ_{c2} Does Not Break the Current	λ_{c3} Does Not Close On Command	λ_{c4} Does Not Make the Current	λ_c Major Failures per10,000 Cycles**	C Average Number of Cycles** per Year	VOLTAGE kV	$C \cdot \lambda_c$ Major Failure per Breaker Year	λ_s Major Failure per Breaker Year	λ_M Total Major Failure per Breaker Year
MAJOR FAILURES PER 10,000 OPEN COMMANDS		MAJOR FAILURES PER 10,000 CLOSE COMMANDS							
0.192	0.048	0.562	0.027	0.829	42.	All Volt.	.00348	.00324***	.00672
0.077	0.000*	0.167	0.009*	0.253	47.	$63 \leq V < 100$	.00119	.00156	.00275
0.161	0.043*	0.781	0.000*	0.985	40.	$100 \leq V < 200$	.00394	.00286	.00680
0.229	0.071*	0.648	0.095*	1.043	39.	$200 \leq V < 300$	.00407	.00407	.00814
0.524	0.113*	1.071	0.057*	1.765	36.	$300 \leq V < 500$	.00635	.00575	.01210
0.506*	0.336*	0.951	0.112*	1.905	45	$500 \leq V$	.00857	.01110	.01967

NOTES
* Small sample size in failure mode data - less than 8 failures
** A cycle is one open command and one close command
*** Approximately 10.6% of these major failures are "breakdown across open pole" and another 2.2% are "closes without command"

TABLE 11 - AVERAGE COST OF SCHEDULED SERVICING of HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 kV FROM FIRST INTERNATIONAL ENQUIRY FOR YEARS 1974-1977
(Includes Ordinary Servicing and Detailed Servicing for All Technology Breakers)

Interval Between Scheduled Servicing Average YEARS	Median	VOLTAGE kV	------Labor Effort------- Average MANHOURS	10	50	90 ---Percentile--- PER BREAKER/YEAR	--Spare Parts Consumed*-- Average MANHOURS	10	50	90 ---Percentile--- PER BREAKER/YEAR
2.3	3.0	63 ≤ V < 100	19.6	5.0	17.5	30.0	55.0	1.0	5.0	60.0
2.0	2.5	100 ≤ V < 200	34.0	10.1	30.0	72.0	38.2	3.0	12.0	60.0
2.0	3.0	200 ≤ V < 300	47.4	15.0	44.0	120.0	87.5	3.0	20.0	90.0
1.4	2.0	300 ≤ V < 500	48.5	13.6	50.0	169.0	72.7	10.0	38.0	157.5

NOTES
* Each country converted the cost of spare parts consumed into equivalent manhours using their labor rate. This resulted in manhours being used as an international currency for both labor effort and spare parts consumed.

DEFINITIONS IN TABLE 11

ORDINARY SERVICING - Servicing scheduled according to given operational conditions which would include a check of the operation measurement of the principal control devices, the measurement of the characteristics of insulation and arc-extinguishing media, cleaning, washing, lubricating, tightening, adjusting, replacing worn parts in accordance with given instructions, and the measurement of the operation characteristics such as lock-out pressures, operating time, insulation of auxiliary circuits, etc

DETAILED SERVICING - Scheduled servicing in accordance with the given instructions necessitated by long service, large number of operations, etc. It will include a more detailed examination of all the parts than carried during Ordinary Servicing.

TABLE 12 - ESTIMATED COST FOR SCHEDULED OVERHAUL of HIGH VOLTAGE CIRCUIT BREAKERS ABOVE 63 kV FROM SECOND INTERNATIONAL ENQUIRY - YEARS 1988-1991
(Includes Scheduled Overhaul for Single Pressure SF6 Circuit Breakers)

Interval Between Scheduled Overhaul Average	10	50	90 --Percentile-- --------YEARS---------	VOLTAGE kV	------Labor Effort------- Average MANHOURS	10	50	90 ---Percentile--- PER BREAKER/YEAR	--Spare Parts Consumed*-- Average MANHOURS	10	50	90 ---Percentile--- PER BREAKER/YEAR
7.6	4.0	6.0	12.0	63 ≤ V < 100	15.3	5.	15.	30.	25.4	2.	24.	61.
8.8	5.0	8.5	15.0	100 ≤ V < 200	17.4	3.	12.	43.	20.7	2.	8.	48.
8.2	4.0	7.9	12.0	200 ≤ V < 300	24.8	5.	15.	50.	31.6	1.	12.	74.
8.2	4.0	7.0	12.0	300 ≤ V < 500	31.0	5.	18.	56.	17.7	2.	8.	48.

NOTES
* Each country converted the cost of spare parts consumed into equivalent manhours using their labor rate. This resulted in manhours being used as an international currency for both labor effort and spare parts consumed.

DEFINITION IN TABLE 12

OVERHAUL - Work done with the objective of repairing or replacing parts, which are found to be below standard by inspection or test or as required by manufacturers maintenance manual, in order to restore the component and/or the circuit-breaker to an acceptable condition.

Report of Circuit Breaker Reliability Survey of Industrial and Commercial Installations

By
A.T. Norris

IEEE Industrial and Commercial Power Systems
Technical Conference
Chicago, Illinois
May 8–11, 1989

Reprinted from IEEE Conference Report
89CH27738-3, pp. 1–16

REPORT OF CIRCUIT BREAKER RELIABILITY SURVEY OF INDUSTRIAL AND COMMERCIAL INSTALLATIONS

Andrew Norris (coordinating Author)[1]

CIRCUIT BREAKER RELIABILITY WORKING GROUP
POWER SYSTEMS RELIABILITY SUBCOMMITTEE
POWER SYSTEMS ENGINEERING COMMITTEE
INDUSTRIAL & COMMERCIAL POWER SYSTEMS DEPARTMENT
IEEE INDUSTRY APPLICATIONS SOCIETY

ABSTRACT

The Reliability Subcommittee of the IEEE Industry Applications Society initiated a survey of the reliability of circuit breakers in industrial and commercial installations in keeping with its commitment to update information on previous surveys. The survey was restricted to circuit breakers that are less than fifteen (15) years old, and excluded molded case breakers, in order to provide information on units of interest and to obtain information on new circuit breaker technologies.

A more detailed explanation on reasons for this survey is included in the appendix.

INTRODUCTION

The results of the survey conducted in 1985 on the reliability of circuit breakers in industrial and commercial installations are summarized in the attached tables. The data obtained includes information on estimated numbers of operations per year for both fault and non-fault situations. Information has also been collected on low voltage circuit breakers comparing static and electro-mechanical integral trip devices.

Each table is discussed to highlight results of the survey. It is the intent of this working group to present the results as updated information on industrial applications and the drawing of definite conclusions is left to the reader.

The reasons for conducting the survey were written down at the beginning and are included in the appendix. Some of these objectives were not achieved due to the small number of participants in the survey. It was not possible to determine the effect of preventive maintenance on failure rate. Insufficient data were submitted on vacuum and single-pressure SF-6 circuit breakers.

[1] The Author is with the University of Missouri - Columbia, Missouri 65211

Members of the Circuit Breaker Reliability Working are Andrew T. Norris (Chairman), James W. Aquilino, William F. Braun, Jr., Charles R. Heising, Don O. Koval, Lou D. Monaghan, Pat O'Donnell, A.D. Patton, and Peter W. Dwyer.

SURVEY RESPONSE

The survey questionnaire, along with the Reasons For Conducting a New Survey on Circuit Breaker Reliability, is included in the appendix.

Due to the low number of responses, 13 plant locations, no attempt was made to separate failures by industry types. While the number of respondents was less than hoped for, the questionnaires were all fully completed for the requested data, with only one (1) "unknown" entry listed which was for a failure duration.

The following list provides a summary of the survey response

No. of Plants	13
No. of Circuit Breakers	2137
Sample Size (unit years)	4097.17
Total no. of Failures	59

The small sample size of the data received limited the results that are being published to four equipment/voltage categories. A special note is made in the tables where the number of failures in a specific category is considered an inadequate sample size. Less than 8 failures has been considered as an inadequate sample size.

OVERALL SUMMARY OF RELIABILITY DATA

Table 1 summarizes the overall results by voltage class. The low number of failures (4) in the 601 volt to 15,000 volt circuit breaker class makes this failure rate data of questionable validity.

This survey shows an increase in the failure rate per unit-year, in the 0-600 volt class, of nearly 3 times the value shown in the 1973 survey. There is, however, a large reduction in the average and maximum failure durations of 30% and 99.5% respectively.

LOCATION

Table 2 shows the effect of outdoor vs. indoor location on the failure rate of 0 - 600 volt circuit breakers. The failure rate was 1.54 times higher for outdoor circuit breakers.

INTEGRAL TRIP

Table 3 compares the integral trip unit type on the failure rate for 0-600 volt circuit breakers. The failure rate of static type integral trip units is 36% of the electromechanical units.

FAILURE MODE

Table 4 shows the failure modes for circuit breakers reported in the survey. It is noted that there were only two instances of units that "failed to open on command", and no occurrences of "closes without command". In the 0-600 volt class all circuit breakers reported had an integral trip device. The circuit breakers with a static integral trip device were split between "failed to close on command" (44%), and "opens without command" (56%). Circuit breakers with electro-mechanical type of integral trip device had a very large portion (93%) of the failures reported to be "failed to close on command".

FAILURE INITIATING CAUSE

Table 5 shows the primary failure initiating cause reported for both 34.5-138kV and 345kV circuit breaker groups as "mechanical breakdown" as 56% and 65% respectively. The 0-600 volt circuit breaker group shows "malfunction of protective relay or tripping device" to be the major category at (93%) for units with electro-mechanical integral tripping. The 0-600 volt units with static type integral tripping reported a roughly even split between "transient overvoltage" and "malfunction of protective relay or tripping device".

FAILURE CONTRIBUTING CAUSE

Table 6 shows that "dust, salt spray, or other contaminant exposure" is the primary reported listing (at 93%) for failure contributing cause for 0-600 volt circuit breakers with electro-mechanical type integral trip. The 0-600 volt circuit breakers with static integral trip had "lack of preventive maintenance" reported for 56% of failures, with the remaining 44% shown as "persistent overload". Entries for other voltage classes are in much lower percentages, except for the "other" category in the 34.5-138kV and 345kV groups.

SUSPECTED FAILURE RESPONSIBILITY

In table 7 the data shows most 0-600 volt breakers with electro-mechanical type of integral trip as having "inadequate physical protection" (93%) as the suspected failure responsibility. The 0-600 volt breakers with static type integral trip reports 56% under "improper operation", and 44% under "inadequate maintenance". The 34.5-138kV and 345kV voltage categories both show "defective component" as the main category.

FAILURE DISCOVERED DURING

Table 8 shows a very large percentage of failures in the 0-600 volt circuit breakers, a total of 96%, as being discovered "during normal operation". The 34.5-138kV class showed a significant percentage of failures (67%) as being discovered "during routing testing/maintenance", while the 345kV breakers were split between "during routing testing/maintenance" and "during normal operation" with 48% in each category.

FAILURES vs. MONTHS SINCE LAST MAINTENANCE

Table 9 shows that most failures occurred within 24 months of the last maintenance.

FAILURE REPAIR METHOD

Table 10 shows that a high percentage of circuit breakers in the 0-600 volt, 601-15,000 volt, and 34.5-138kV ratings were "repaired failed component in place or sent out for repair".

The 345kV group of circuit breakers shows the highest number (44%) as "replaced failed unit with spare". This large percentage is considered questionable since an inspection of the failed component entries showed in some cases that a failed component, such as an air compressor, was reported as "replaced failed unit with spare".

REPAIR URGENCY

It is of particular interest that, in Table 11, only 7% of the 59 failures reported for all voltage categories listed the repair urgency as requiring working on a round-the-clock bases. This may be due, at least in part, to the fact that two of the voltage classes (0-600 volt, and 601-15,000 volt) containing 45% of the total failures, and had <u>maximum</u> failure durations of 4 hours.

The 34.5-138kV and 345kV circuit breakers, with their longer failure durations, also show nearly all repair work as normal working hours.

POPULATION OF CIRCUIT BREAKERS vs. MAINTENANCE QUALITY AND NORMAL MAINTENANCE CYCLE

Table 12 shows the majority of respondents (53%) considered themselves as having a "fair" maintenance quality, while 39% considered their maintenance

quality as "excellent". All of the respondents who listed their maintenance quality as excellent had a normal maintenance cycle of 0-24 months. The respondents with "fair" maintenance quality were split between categories with 37% (by unit-year) showing 0-24 month, 28% (by unit-year) showing more then 24 months and, interestingly enough, 35% with No preventive maintenance.

OVERALL CIRCUIT BREAKER OPERATIONS PER YEAR DATA

The listing of "overall circuit breaker operations data" has been entered in three different tables.

Table 13a shows the data entered in a non-weighted format. The fault, and non-fault, operations per year are based on non-weighted numbers. The non-weighted values were obtained by counting each population data line entry as one unit (regardless of how many circuit breakers or unit-years were reported in that line). The average number of operations for each entry line were summed and the result divided by the number of line entries.

Table 13b shows the data weighted by the number of circuit breakers. The fault and non-fault operations per year are based on the actual number of circuit breakers reported, regardless of time in service. The average number of operations for each entry line was multiplied times the number of circuit breakers reported for that line. The resulting values were summed and the total was then divided by the number of circuit breakers reported in that voltage category.

Table 13c shows the data weighted by the number of unit-years. The fault and non-fault operations per year are based on the number of circuit breakers reported times their number of years in service (unit-years). The unit-years for each circuit breaker times the average operations per year was summed and the result divided by the total number of unit-years reported in that voltage category.

With the exception of the 0-600 volt category, the average number of operations per year remained reasonably consistent over the three tables.

Table 1 - OVERALL CIRCUIT BREAKER RELIABILITY DATA

	0-600 Volt * Air Magnetic	601-15,000 Volt *** Air Magnetic	34.5-138 kV Bulk Oil	345 kV Air Blast & SF-6 (2 presure)
Sample Size (number of units)	1695	315	64	51
Sample Size (unit-years)	2941.24	694.76	192.50	256.00
Total Fault Operations (for all unit-years)	225	343	103	434
Total Non-Fault Operations (for all unit-years)	24604	24914	4320	6200
Number of Failures	23	** 4	9	23
Failure Rate - Failures/Unit-Year	0.00782	** 0.00576	0.04675	0.08984
Failure Duration (Hours/Failure)		**		
Average	2.8	2.25	41.11	171.45
Minimum	0.5	1	1	1
Median	4	2	3	150
Maxumum	4	4	240	720

* Excludes Molded Case
** Small Sample Size - less than 8 failures (or data points)
*** Zero failures in 2.67 unit-years reported for Vacuum 601-15,000 volt (not included in this table)

NOTE: The "Total Fault Operations" and "Total Non-Fault Operations" were determined by taking the Unit-years (for each circuit breaker reported) times it's average number of operations (Fault or Non-Fault) per year, and adding the values for all circuit breakers in that catagory.

*
Table # 2 CIRCUIT BREAKERS, 0-600 VOLT
OUTDOOR versus INDOOR LOCATION

	Outdoor	Indoor
Sample Size (unit-years)	873.57	2067.67
Number of Failures	9	14
Failure Rate - Failures/Unit-Year	0.0103	0.00677

* Excludes Molded Case

*
Table # 3 CIRCUIT BREAKERS, 0-600 VOLT
EFFECT OF INTEGRAL TRIP TYPE

	Static	Electro-mechanical
Sample Size (unit-years)	1888.49	1052.75
Number of Failures	9	14
Failure Rate - Failures/Unit-Year	0.00477	0.0133

* Excludes Molded Case

TABLE # 4 - CIRCUIT BREAKERS
VOLTAGE VS. FAILURE MODE

	0-600 VOLT * Air Magnetic Static	0-600 VOLT * Air Magnetic Electro-mech	601-15KV Air Magnetic	34.5KV-138KV Bulk Oil	345KV Air Blast & SF-6 (2 presure)
FAILED TO CLOSE ON COMMAND	4 44%	13 93%	-0-	3 33%	-0-
FAILED TO CLOSE AND LATCH	-0-	-0-	-0-	1 11%	-0-
FAILED TO OPEN ON COMMAND	-0-	-0-	2 50%	-0-	-0-
CLOSES WITHOUT COMMAND	-0-	-0-	-0-	-0-	-0-
OPENS WITHOUT COMMAND	5 56%	-0-	1 25%	-0-	7 30%
FAILED TO BREAK CURRENT WHEN OPENING	-0-	-0-	-0-	-0-	-0-
DAMAGED WHILE SUCCESSFULLY OPENING	-0-	-0-	1 25%	-0-	-0-
DAMAGED WHILE CLOSING	-0-	-0-	-0-	-0-	-0-
FAILED TO CARRY CURRENT	-0-	-0-	-0-	1 11%	-0-
FAULT TO GROUND, OR PHASE TO PHASE (NOT WHILE OPENING OR CLOSING)	-0-	-0-	-0-	-0-	-0-
FAULT ACROSS OPEN CONTACTS (NOT WHILE OPENING OR CLOSING)	-0-	-0-	-0-	-0-	-0-
LOSS OF VACUUM (FOR VACUUM BREAKERS)	-0-	-0-	-0-	-0-	-0-
OTHER FAILURE REQUIRING REMOVAL FROM SERVICE WITHIN 30 MINUTES	-0-	-0-	-0-	-0-	11 48%
OTHER FAILURE NOT REQUIRING REMOVAL FROM SERVICE	-0-	1 7%	-0-	3 33%	3 13%
UNKNOWN	-0-	-0-	-0-	1 11%	2 9%
TOTAL FAILURES	9 100%	14 100%	4 100%	9 100%	23 100%

* Excludes Molded Case

TABLE # 5 - CIRCUIT BREAKERS
VOLTAGE VS. FAILURE INITIATING CAUSE

	0-600 VOLT * Air Magnetic Static	0-600 VOLT * Air Magnetic Electro-mech	601-15KV ** Air Magnetic	34.5KV-138KV Bulk Oil	345KV Air Blast & SF-6 (2 presure)
TRANSIENT OVERVOLTAGE-SUCH AS LIGHTNING, SWITCHING SURGES, OR SYSTEM FAULTS	4 44%	-0-	1 25%	-0-	-0-
INSULATION BREAKDOWN	-0-	-0-	-0-	-0-	1 4%
MECHANICAL BURNOUT, FRICTION, OR SEIZING OF MOVING PARTS	-0-	-0-	-0-	-0-	1 4%
MECHANICAL BREAKDOWN - SUCH AS CRACKING, LOOSENING, ABRADING, OR DEFORMING OF STATIC OR STRUCTURAL PARTS	-0-	-0-	1 25%	5 56%	15 65%
PHYSICAL DAMAGE OR SHORTING FROM OUTSIDE SOURCE - SUCH AS VEHICULAR ACCIDENT	-0-	-0-	-0-	-0-	-0-
ELECTRICAL FAULT OR MALFUNCTION	-0-	-0-	1 25%	1 11%	3 13%
MALFUNCTION OF PROTECTIVE RELAY OR TRIPPING DEVICE	5 56%	13 93%	-0-	1 11%	-0-
OTHER AUXILIARY DEVICE MALFUNCTION	-0-	-0-	-0-	2 22%	-0-
LOW, OR NO, AUXILIARY VOLTAGE - FOR CIRCUITS SUCH AS AIR COMPRESSORS, AND SF-6 HEATERS	-0-	-0-	-0-	-0-	-0-
OTHER	-0-	1 7%	1 25%	-0-	3 13%
TOTAL FAILURES	9 100%	14 100%	4 100%	9 100%	23 100%

* Excludes Molded Case

TABLE # 6 - CIRCUIT BREAKERS
VOLTAGE VS. FAILURE CONTRIBUTING CAUSE

	0-600 VOLT * Air Magnetic Static	0-600 VOLT * Air Magnetic Electro-mech	601-15KV ** Air Magnetic	34.5KV-138KV Bulk Oil	345KV Air Blast & SF-6 (2 presure)
OVERLOAD - PERSISTENT	4 44%	-0-	1 25%	-0-	-0-
EXTREME HEAT	-0-	-0-	-0-	-0-	-0-
EXTREME COLD	-0-	-0-	-0-	-0-	3 13%
SEVERE WEATHER - SUCH AS WIND, RAIN, SNOW, OR SLEET	-0-	-0-	-0-	-0-	-0-
ABNORMAL MOISTURE	-0-	-0-	-0-	-0-	-0-
AGRESSIVE CHEMICALS	-0-	-0-	-0-	-0-	-0-
DUST, SALT SPRAY, OR OTHER CONTAMINANT EXPOSURE	-0-	13 93%	-0-	-0-	-0-
NORMAL DETERIORATION FROM AGE	-0-	-0-	-0-	2 22%	1 4%
LUBRICANT LOSS, OR DEFICIENCY	-0-	-0-	1 25%	1 11%	-0-
IMPROPER OPERATING OR TEST PROCEDURE	-0-	-0-	-0-	-0-	1 4%
TRIPPING SOURCE DEFICIENT	-0-	-0-	-0-	-0-	-0-
LACK OF PREVENTIVE MAINTENANCE	5 56%	-0-	1 25%	1 11%	-0-
OTHER	-0-	1 7%	1 25%	5 56%	18 78%
TOTAL FAILURES	9 100%	14 100%	4 100%	9 100%	23 100%

* Excludes Molded Case

TABLE # 7 - CIRCUIT BREAKERS
VOLTAGE VS. SUSPECTED FAILURE RESPONSIBILITY

	0-600 VOLT * Air Magnetic Static	0-600 VOLT * Air Magnetic Electro-mech	601-15KV ** Air Magnetic	34.5KV-138KV Bulk Oil	345KV Air Blast & SF-6 (2 presure)
DEFECTIVE COMPONENT	-0-	-0-	1 25%	4 44%	13 57%
IMPROPER HANDLING/SHIPPING	-0-	-0-	-0-	-0-	-0-
POOR INSTALLATION/TESTING	-0-	-0-	-0-	1 11%	1 4%
INADEQUATE MAINTENANCE	4 44%	-0-	-0-	1 11%	-0-
IMPROPER OPERATION	5 56%	-0-	1 25%	1 11%	-0-
IMPROPER APPLICATION	-0-	1 7%	-0-	-0-	-0-
INADEQUATE PHYSICAL PROTECTION	-0-	13 93%	-0-	-0-	-0-
OUTSIDE AGENCY (SUCH AS VEHICULAR ACCIDENT)	-0-	-0-	-0-	-0-	-0-
OTHER	-0-	-0-	2 50%	2 22%	4 17%
UNKNOWN	-0-	-0-	-0-	-0-	5 22%
TOTAL FAILURES	9 100%	14 100%	4 100%	9 100%	23 100%

* Excludes Molded Case

TABLE # 8 - CIRCUIT BREAKERS
VOLTAGE VS. "FAILURE DISCOVERED DURING"

	0-600 VOLT * Air Magnetic Static	Electro-mech	601-15KV ** Air Magnetic	34.5KV-138KV Bulk Oil	345KV Air Blast & SF-6 (2 presure)
DURING ROUTINE TESTING/MAINTENANCE	-0-	1 7%	1 25%	6 67%	11 48%
DURING NORMAL OPERATION	9 100%	13 93%	3 75%	3 33%	11 48%
OTHER	-0-	-0-	-0-	-0-	1 4%
TOTAL FAILURES	9 100%	14 100%	4 100%	9 100%	23 100%

* Excludes Molded Case

** Small Sample Size - less than 8 failures (or data points)

TABLE # 9 - CIRCUIT BREAKERS
FAILURES VS. MONTHS SINCE LAST MAINTENANCE

***	0-600 VOLT * Air Magnetic Static	Electro-mech	601-15KV ** Air Magnetic	34.5KV-138KV Bulk Oil	345KV Air Blast & SF-6 (2 presure)
0 - 24 MONTHS	-0-	14 100%	2 50%	8 89%	17 74%
OVER 24 MONTHS	9 100%	-0-	2 50%	-0-	6 26%
NO PREVENTIVE MAINTENANCE	-0-	-0-	-0-	1 11%	-0-
TOTAL FAILURES	9 100%	14 100%	4 100%	9 100%	23 100%

* Excludes Molded Case

** Small Sample Size - less than 8 failures (or data points)

*** The survey requested data for 0-12 month and 12-24 month periods. Due to the uncertainty about which of these two periods should be used for entries of 12 months since maintenance, they were combined into a single entry of 0-24 months.

TABLE # 10 - CIRCUIT BREAKERS
VOLTAGE VS. FAILURE REPAIR METHOD

	0-600 VOLT * Air Magnetic Static	0-600 VOLT * Air Magnetic Electro-mech	601-15KV ** Air Magnetic	34.5KV-138KV Bulk Oil	345KV Air Blast & SF-6 (2 presure)
REPAIRED FAILED COMPONENT IN PLACE OR SENT OUT FOR REPAIR	8 89%	13 93%	3 75%	7 78%	7 30%
REPLACED FAILED UNIT WITH SPARE	1 11%	1 7%	1 25%	2 22%	*** 10 43%
OTHER	-0-	-0-	-0-	-0-	6 26%
TOTAL FAILURES	9 100%	14 100%	4 100%	9 100%	23 100%

* Excludes Molded Case

** Small Sample Size - less than 8 failures (or data points)

*** In some cases a failed component, not the complete breaker, was replaced with a spare.

TABLE # 11 - CIRCUIT BREAKERS
VOLTAGE VS. FAILURE REPAIR URGENCY

	0-600 VOLT * Air Magnetic Static	0-600 VOLT * Air Magnetic Electro-mech	601-15KV ** Air Magnetic	34.5KV-138KV Bulk Oil	345KV Air Blast & SF-6 (2 presure)
WORKING ROUND-THE-CLOCK	2 22%		1 25%	1 11%	-0-
NORMAL WORKING HOURS	7 78%	14 100%	3 75%	8 89%	23 100%
LOW PROIRITY	-0-	-0-	-0-	-0-	-0-
TOTAL FAILURES	9 100%	14 100%	4 100%	9 100%	23 100%

* Excludes Molded Case

** Small Sample Size - less than 8 failures (or data points)

TABLE # 12 - CIRCUIT BREAKERS
POPULATION OF CIRCUIT BREAKERS VERSUS
MAINTENANCE QUALITY & NORMAL MAINTENANCE CYCLE

MAINTENAN QUALITY	MAINTENANCE, NORMAL CYCLE 0 - 24 MONTHS *	MORE THEN 24 MONTHS	NO PREVENTIV MAINTENAN	TOTAL	
	POPULATION: UNIT-YEARS				
EXCELLENT	1198.25	383	-0-	1581.25	39%
FAIR	797.99	606.59	749.34	2153.92	53%
POOR	-0-	-0-	-0-	-0-	0%
NONE	-0-	-0-	362	362	9%

* The survey requested data for 0-12 month and 12-24 month periods. Due to the uncertainty about which of these two periods should be used for entries of 12 months since maintenance, they were combined into a single entry of 0-24 months.

Table 13a - OVERALL CIRCUIT BREAKER OPERATIONS DATA (Non-weighted)

	0-600 Volt * Air Magnetic	601-15,000 Volt Air Magnetic	34.5-138 kV Bulk Oil	345 kV Air Blast & SF-6 (2 presure)
Fault Operations/Year				
Average	0.175	0.3481	0.6945	1.1325
Minimum	0	0	0.05	0.2
Median	0.05	0.0769	0.75	2
Maxumum	1	1	2	2
Non-Fault Operations/Year				
Average	19.2834	47.5357	24.125	30
Minimum	0	0.5	3	10
Median	1.667	5	15	30
Maxumum	100	400	100	50

* Excludes Molded Case

To get the non-weighted values for Average Fault (and Non-Fault) Operations per year, each line entry was counted as one unit (reguardless of how many circuit breakers were reported in that line). The average number of operations for each entry line were summed and the result divided by the number of line entries. Twenty (20) line entries would be counted as 20 units, even though each line might represent 5 circuit breakers.

Table 13b - OVERALL CIRCUIT BREAKER OPERATIONS DATA (weighted by number of breakers)

	0-600 Volt * Air Magnetic	601-15,000 Volt Air Magnetic	34.5-138 kV Bulk Oil	345 kV Air Blast & SF-6 (2 presure)
Fault Operations/Year				
Average	0.0174	0.5898	0.4877	1.2341
Minimum	0	0	0.05	0.2
Median	0	1	0.75	2
Maxumum	1	1	2	2
Non-Fault Operations/Year				
Average	5.0932	27.1841	20.0156	35.098
Minimum	0	0.5	3	10
Median	5	25	20	30
Maxumum	100	400	100	50

* Excludes Molded Case

To get the weighted values (weighted by number of circuit breakers) for Average Fault, and Non-Fault operations, the number of operations for each entry line is multiplied by the number of circuit breakers reported in that line. The product (number of circuit breakers times average operations) from each line was summed and the result divided by the total number of circuit breakers reported in that catagory.

Table 13c - OVERALL CIRCUIT BREAKER OPERATIONS DATA (weighted by number of unit-years)

	0-600 Volt * Air Magnetic	601-15,000 Volt Air Magnetic	34.5-138 kV Bulk Oil	345 kV Air Blast & SF-6 (2 presure)
Fault Operations/Year				
Average	0.0767	0.4936	0.5375	1.6948
Minimum	0	0	0.05	0.2
Median	0.02	0.5	0.5	2
Maxumum	1	1	2	2
Non-Fault Operations/Year				
Average	8.3652	35.86	22.439	32.0313
Minimum	0	0.5	3	10
Median	1.6667	5	20	30
Maxumum	100	400	100	50

* Excludes Molded Case

To get the weighted values (weighted by number of unit-years) for Average Fault, and Non-Fault operations, the number of operations for each survey line entry is multiplied by the number of unit-years (circuit breakers reported in that line times the number years in service). The product (number of unit-years times average operations) from each line was summed and the result divided by the total number of unit-years reported in that catagory.

APPENDIX

REASONS FOR CONDUCTING A NEW SURVEY ON CIRCUIT BREAKER RELIABILITY

by Circuit breaker Reliability Working Group
C. R. Heising, Coordinating Author
A. T. Norris, Chairman
J. W. Aquilino L. G. Monaghan
R. N. Bell P. O'Donnell
W. F. Braun A. D. Patton

The main purpose of this reliability survey is to identify failure data and the effect of pertinent factors on important classes and types of circuit breakers, thus providing the designer and planner the valuable basic information needed to install a reliable and economic industrial or commercial power system.

Previous IEEE-IAS circuit breaker reliability surveys of industrial & commercial installations were published in 1962 and in 1973/74. The latter has been included in IEEE Standard No. 493-1980 - "Recommended Practice for the Design of Reliable Industrial & Commercial Power Systems." Pertinent information from the new survey will be included in future revisions of IEEE Standard No. 493.

Some of the important objectives in this new survey are: 1. Obtain failure mode data, 2. Obtain estimates of the number of operating cycles per year, 3. Obtain data on static trip devices for low voltage circuit breakers, 4. Obtain information on the effect of preventive maintenance on failure rate, 5. Obtain better information on suspected failure responsibility, failure initiating cause, and failure contributing cause, and 6. Obtain pertinent information on new circuit breaker technologies.

33% or more of the failures reported in the 1973/74 survey did not contain information on suspected failure responsibility, failure initiating cause, and failure contributing cause. It is hoped that this can be improved upon in the new survey. This is considered important information when trying to improve the reliability of circuit breakers used on industrial & commercial power systems. In the 1973/74 survey 23% of the failures were blamed on the manufacturer and 23% were blamed on inadequate maintenance and 36% were unknown. These were the three largest causes of failures. Inadequate maintenance is an area that an industrial or commercial user can do something about; and any pertinent information on this subject will be requested.

The 1973/74 survey did not collect information on the estimated number of operating cycles per year. This is important information when trying to estimate the probability of a circuit breaker successfully operating when commanded to do so. This information will permit a reliability assessment versus duty application.

The 1973/74 survey did not collect low voltage circuit breaker data on whether of not a static trip device was used. This information is of interest to designers of power systems where there is much concern about failure rate of solid state versus electromechanical trip devices.

Approximately 30% of the circuit breakers in the 1973/74 survey were over ten years old. Circuit breakers more than 15 years old may not be typical of what is being used in the design of new power systems.

Various classes and types of circuit breakers in the 1973/74 survey had significantly different distributions of the various failure modes. Updated information on this subject is of interest to designers of power systems.

Reliability information on medium and high voltage circuit breakers using the newer technologies is of interest to designers of power systems. This includes vacuum and SF6-puffer circuit breakers.

Switchgear bus is not included in this survey. A separate survey was published on this subject in 1979. Protective relays, fuses, and switches are not included in this survey. A survey in 1976 on these equipment categories asked for information that many industrial and commercial users did not have readily available; and the survey was unsuccessful. A limited amount of information is contained in the 1973/74 survey on disconnect switches, relays, and fuses.

CIRCUIT BREAKERS

COMPANY NAME AND PLANT: ____________________

INDUSTRY TYPE: ____________________

PERIOD REPORTED - FROM: MONTH __________ YEAR __________

TO: MONTH __________ YEAR __________

LOCATION: ____________________

<u>TOTAL POPULATION</u>

A	B	C	D	E	F	G	H	I	J	K	L	M
IDENTIFICATION NUMBER	CIRCUIT BREAKER TYPE (Insert Code)	NUMBER OF BREAKERS	USED PRIMARILY AS MOTOR STARTER (Y-YES, N-NO)	LINE-TO-LINE VOLTAGE (kV)	LOCATION (I-INDOOR, O-OUTDOOR)	INTEGRAL TRIP DEVICE* (Y-YES, N-NO)	INTEGRAL TRIP IS (S-STATIC, EM-ELECTRO MECH)	EST. AVERAGE # OF NON-FAULT OPERATIONS/YEAR/BREAKER**	EST. AVERAGE # OF FAULT OPERATIONS/YEAR/BREAKER**	MAINTENANCE CYCLE (Insert Code)	MAINTENANCE QUALITY (Insert Code)	BRIEF DESCRIPTION OF MAINTENANCE

* IF TRIP INITIATION UNIT IS AN INTEGRAL PART OF THE BREAKER, INCLUDE ANY FAILURE OF THE TRIP UNIT AS A BREAKER FAILURE.

** CONSIDER EACH OPEN/CLOSE CYCLE AS ONE (1) OPERATION. INCLUDE OPERATIONS DURING MAINTENANCE.

CIRCUIT BREAKER

COMPANY NAME AND PLANT: ____________________

<u>FAILED UNIT DATA</u> - Fill in One Line for Each Failure

A	B	C	D	E	F	G	H	I	J	K
IDENTIFICATION NUMBER (FROM TOTAL POPULATION)	FAILURE DISCOVERED (INSERT CODE)	FAILURE INITIATING CAUSE (INSERT CODE)	FAILURE CONTRIBUTING CAUSE (INSERT CODE)	SUSPECTED FAILURE RESPONSIBILITY (INSERT CODE)	FAILURE MODE (INSERT CODE)	MONTHS SINCE LAST MAINTENANCE (INSERT CODE)	REPAIR URGENCY (INSERT CODE)	FAILURE DURATION-HOURS	REPAIR OR REPLACE (INSERT CODE)	FAILED COMPONENT

CIRCUIT BREAKER RELIABILITY SURVEY
SURVEY CODE

Total Population Form

Circuit breaker Type (B)
1. Air Magnetic
2. Vacuum
3. Bulk Oil
4. Air Blast
5. "Puffer" Type SF-6
6. All SF-6 other then "Puffer"
7. Other

Normal Maintenance Cycle (K)
1. 0-12 months
2. 12-24 months
3. Over 24 months
4. No preventive maintenance

Maintenance Quality (L)
Your estimate of Preventive Maintenance Quality:
1. Excellent
2. Fair
3. Poor
4. None

Failed Unit Form

Failure Discovered (B)
1. During Routine Testing/ Maintenance
2. During Normal Operation
3. Other

Failure Initiating Cause (C)
1. Transient overvoltage - such as lightning, switching surges, or system faults.
2. Insulation Breakdown.
3. Mechanical burnout, friction, or seizing of moving parts.
4. Mechanical breakdown - such as cracking, loosening, abrading, or deforming of static or structural parts.
5. Physical damage or shorting from outside source - such as vehicular accident.
6. Electrical fault or malfunction.
7. Malfunction of protective relay or tripping device.
8. Other auxiliary device Malfunction.
9. Low, or no, auxiliary voltage - for circuits such as air compressors, and SF-6 heaters.
10. Other

Failure Contributing Cause (D)
1. Overload - persistent
2. Extreme hear (ambient temperature if known ____ deg. C)
3. Extreme Cold (ambient temperature if known ____ deg. C)
4. Severe weather - such as wind, rain, snow, or sleet.
5. Abnormal moisture.
6. Aggressive chemicals.
7. Dust, salt spray, or other contaminant exposure.
8. Normal deterioration from age.
9. Lubricant loss, or deficiency.
10. Improper operating or test procedure.
11. Tripping source deficient.
12. Lack or preventive maintenance.
13. Other

Suspected Failure Responsibility (E)
1. Defective component
2. Improper handling/shipping
3. Poor installation/testing
4. Inadequate maintenance
5. Improper operation
6. Improper application
7. Inadequate physical protection
8. Outside agency (such as vehicular accident)
9. Other
10. Unknown

Failure Mode (F)
1. Failed to close on command
2. Failed to close and latch
3. Failed to open on command
4. Closes without command
5. Opens without command
6. Failed to break current when opened
7. Damaged while successfully opening
8. Damaged while closing
9. Failed to carry current
10. Fault to ground, or phase to phase (not while opening or closing)
11. Fault across open contacts (not while opening or closing)
12. Loss of vacuum (for vacuum breakers)
13. Other failure requiring removal from service within 30 minutes
14. Other failure not requiring immediate removal from service
15. Unknown

Months Since Last Maintenance (G)
1. 0 - 12 months
2. 12 - 24 months
3. Over 24 months
4. No preventive maintenance

Repair Urgency (H)
1. Working round-the-clock
2. Normal working hours
3. Low priority

Repair Or Replace (J)
1. Repaired failed component in place or sent out for repair
2. Replaced failed unit with spare
3. Other

REFERENCES

[1] ANSI/IEEE Standard 493-1980, "IEEE Recommended Practice For Design of Reliable Industrial and Commercial Power Systems".

Reliability Survey of 600 to 1800 kW Diesel and Gas-Turbine Generating Units

By
Clayton A. Smith, Michael D. Donovan, and Michael J. Bartos

Conference Record of the IEEE Industrial and Commercial Power Systems Technical Conference
Chicago, Illinois
May 8–11, 1989

IEEE Transactions on Industry Applications
July/August 1990, pp. 741–755

Reliability Survey of 600 to 1800 kW Diesel and Gas-Turbine Generating Units

CLAYTON A. SMITH, MICHAEL D. DONOVAN, ASSOCIATE MEMBER, IEEE, AND MICHAEL J. BARTOS

Abstract — In 1988 the U.S. Army Engineering and Housing Support Center (EHSC) sponsored a study of the reliability, availability, and maintainability (RAM) characteristics of diesel and gas-turbine power systems producing less than 2 MW. The study, conducted by ARINC Research Corporation, included collection and examination of source data for power systems at commercial and military facilities operating in continuous or standby service. A data base of system, subsystem, and component RAM data was established. These data will be useful in the design of primary and standby power systems for military or commercial facilities.

Introduction

THE U.S. Army Engineering and Housing Support Center (EHSC) sponsored a study [7] of the reliability, availability, and maintainability (RAM) characteristics of small diesel and gas-turbine power systems. The study, conducted by ARINC Research, produced a data base of system, subsystem, and component RAM data for industrial and military power systems in both continuous and standby service. An updated RAM data base was needed to support the analysis of power systems at command, control, communications, and intelligence (C^3I) installations worldwide. EHSC wanted higher confidence in the validity of the power-system reliability data used to analyze C^3I system reliability. Currently available RAM data were outdated and were not tailored to EHSC's specific requirements. Further, these data did not permit identifying component failure rates in alternative prime-mover designs.

The primary objective was to obtain data reflecting the reliability improvements resulting from advances in power-plant (prime-mover) technology since completion of the last comprehensive RAM study more than 15 years earlier. An additional objective was to provide data on the major components that failed in each system, together with data on the reliability of the prime mover. The information will be used in the evaluation of C^3I power-generation systems.

The prime movers of interest were diesel and gas-turbine generators ranging from 600 to 1800 kW. The diesel-generator configurations evaluated included both packaged systems and units with auxiliary support systems. Each of these types was categorized as standby and continuous duty. Because most gas-turbine systems in the size range of interest are configured as packaged units, the gas-turbine generators were categorized only by type of duty. Thus six categories were addressed:

- continuous-duty auxiliary diesels,
- standby auxiliary diesels,
- continuous-duty package diesels,
- standby package diesels,
- continuous-duty gas turbines,
- standby gas turbines.

Methodology

The data collection comprised five tasks: 1) review existing data bases and reports, 2) identify data sources, 3) collect field data, 4) reduce data and prepare data base, and 5) calculate RAM statistics. These tasks are described in the following subsections.

Review Existing Data Bases and Reports

The results of previous and ongoing efforts in the collection of RAM data were reviewed to determine their applicability to the selected diesel and gas-turbine categories. Data bases such as the Government Industry Data Exchange Program (GIDEP) [1] and the Institute of Nuclear Power Operations (INPO) Nuclear Plant Reliability Data System (NPRDS) [5] were investigated, but they were found to contain minimal detail on power plants in the size ranges addressed by the study. Several manufacturers provided the results of studies on reliability, starting reliability, and unit availability conducted in preparation for customer presentations or proposals. The RAM measures from these studies were not included in the data base, because the objectivity and accuracy of the data could not be validated.

Identify Candidate Data Sources

Three methods were used to identify as candidate data sources the industrial and military facilities that operated diesel and gas-turbine power systems in the specified categories. Equipment manufacturers and distributors were asked to provide lists of customers having power systems that met the category definitions. U.S. military and Government agencies were similarly requested to provide names of equipment operators and sources of maintenance data. In addition, industrial directories were used to identify facilities representing typi-

Paper ICPSD 89-02, approved by the Power Systems Engineering Committee of the IEEE Industry Applications Society for presentation at the 1989 Industrial and Commercial Power Systems Annual Technical Conference, Detroit, MI, April 29-May 3. Manuscript released for publications January 9, 1990.

C. A. Smith and M. D. Donovan are with ARINC Research Corporation, 2551 Riva Road, Annapolis, MD 21401.

M. J. Bartos is with the U.S. Army Engineering and Housing Support Center, Fort Belvoir, VA 20060.

IEEE Log Number 9035434.

USER SURVEY: DIESEL AND GAS-TURBINE GENERATORS

User/Company:
Address:
Contact:
Telephone: ( )
Date:
Application:
Staffing (No. of personnel and titles):

Items to Address:

How many units do you have on-site:
What are their ratings?
Are units standby or in continuous use?

	Yes	No
Is there a central data bank for maintenance information?		
Do you collect maintenance data?		
Do you collect operating data?		
Do you record attempted and successful starts?		
Do you keep logs for scheduled maintenance?		
Do you have records of failure events?		
Have there been at least five failures to the unit?		
Do you track administrative and logistic time?		
Can these data be sent to us for this effort?		
Can ARINC Research obtain permission to review these records?		
Is there a maintenance program in use?		
If yes, is it the manufacturer's program?		
Are spares kept on site?		

Remarks: (Include brief history and line diagram of plant)

User Code:

Fig. 1. User survey form.

cal power-system users, such as computer centers, small utility sites, and cogeneration plants. The candidate data sources identified through these surveys were listed in a project data base for sorting and screening during the data collection task.

Collect Data

Potential data sources were screened by means of a structured telephone survey technique, using the questions shown in Fig. 1, to identify candidate power plants for data collection. The objective of this screening was to determine the applicability, availability, and quality of operational, maintenance, and failure data. Plants were selected from a wide variety of applications (e.g., electric utilities, cogenerators, hospitals, airfields, military installations, and computer and communication facilities) to represent a range of variables such as manufacturer, plant usage, age, environment, and maintenance practices. Where possible, plants with at least ten years of operation and maintenance history were selected.

Selected power-plant operators with formal data collection systems were requested to mail facility descriptions and historical records of their operation and maintenance logs. Follow-up technical questions to clarify data interpretation were directed, via telephone conversations, to senior facility personnel.

The problem most frequently encountered in obtaining data from participating facilities was the level of effort required by the plant staff to assemble and reproduce the necessary records. To ensure the acquisition of representative data, site visits were made to facilities that could not respond to the mailing requests. Technical personnel experienced in plant operation and maintenance conducted these visits. In addition to records collection, visits typically included structured interviews with senior operations and maintenance personnel to obtain additional insights into failure events and maintenance tasks.

Twenty-two plants participated in the study, providing data on 71 power systems. The data represented 708 unit-years of operating experience, and all plants provided data for periods of 3 years or longer.

Develop Data Base

The source data on maintenance and failure events were arranged in a consistent record format for computer entry and validation. Data reduction was performed by examining events

TABLE I
RAM STATISTICS

RAM Measures	Formula Based on Period Hours	Formula Based on Operating Hours
Failure Rate (FR) (Failures per year)	$\frac{\text{No. of Failures}}{\text{Period Hours}} \times 8{,}760$	$\frac{\text{No. of Failures}}{\text{Operating Hours}} \times 8{,}760$
Mean Time Between Failures (MTBF) (Hours)	$\frac{\text{Period Hours}}{\text{No. of Failures}}$	$\frac{\text{Operating Hours}}{\text{No. of Failures}}$
Mean Time To Repair (MTTR) (Hours)	$\frac{\text{Total Repair Time}}{\text{No. of Failures}}$	$\frac{\text{Total Repair Hours}}{\text{No. of Failures}}$
Mean Time Between Planned Outages (MTBPO) (Hours)	$\frac{\text{Period Hours}}{\text{No. of Planned Outages}}$	$\frac{\text{Operating Hours}}{\text{No. of Planned Outages}}$
Mean Time To Maintain (MTTM) (Hours)	$\frac{\text{Planned Outage Hours}}{\text{No. of Planned Outages}}$	$\frac{\text{Planned Outage Hours}}{\text{No. of Planned Outages}}$
Mean Time Between Outages (MTBO) (Hours)	$\frac{\text{Period Hours}}{\text{No. of Outages}}$	$\frac{\text{Operating Hours}}{\text{No. of Outages}}$
Mean Downtime (MDT) (Hours)	$\frac{\text{Repair Hours + Planned Outage Hours}}{\text{No. of Outages}}$	$\frac{\text{Repair Hours + Planned Outage Hours}}{\text{No. of Outages}}$
Mean Time Between Corrective Maintenance (MTBCM) (Hours)	$\frac{\text{Period Hours}}{\text{No. of CMs}}$	$\frac{\text{Operating Hours}}{\text{No. of CMs}}$
Mean Time To Perform Corrective Maintenance (MTTCM) (Hours)	$\frac{\text{Corrective Maintenance Hours}}{\text{No. of CMs}}$	$\frac{\text{Corrective Maintenance Hours}}{\text{No. of CMs}}$
Availability, Operational (AO)	$\frac{\text{Period Hours − Repair Time − Planned Outage Hours}}{\text{Period Hours}}$	$\frac{\text{Operating Hours}}{\text{Operating Hours + Repair Hours + Planned Outage Hours}}$
Availability, Inherent (AI)	$\frac{\text{Period Hours − Repair Hours}}{\text{Period Hours}}$	$\frac{\text{Operating Hours}}{\text{Operating Hours + Repair Hours}}$
Reliability for 24 hours (R24)	$e^{-24/MTBF}$	$e^{-24/MTBF}$
Reliability for 720 hours (R720)	$e^{-720/MTBF}$	$e^{-720/MTBF}$

in the operating and maintenance records to identify the subsystem and component, the type of outage, the impact of the failure, and the action required to complete the maintenance. This information was coded according to the equipment, failure-impact, outage-type, and action codes listed in Appendix I.

Summary descriptions of each maintenance event were also prepared to provide insight into failure modes. Operating data for each unit—such as period hours, operating hours, starts, and start failures—were extracted from operating logs.

The event records produced by the data-reduction process were entered into a microcomputer data base. The data base architecture, developed with a commercially available data base management system, included features for automated checking for data-entry errors or inconsistencies. Following data entry, samples of records were randomly selected for validation against the raw data, ensuring consistency in application of the event coding scheme during data reduction.

Calculate RAM Statistics

The maintenance-event and operational data and the formulas shown in Table I were used to calculate RAM statistics for each of the six categories of power systems. The terms used in the formulas are defined in Table II.

RAM statistics were also calculated for subsystems and components in each category on the basis of both period hours and unit operating hours. Subsystem and component measures included failure rate (FR), mean time between failures (MTBF), mean time between corrective maintenance (MTBCM), mean time to perform corrective maintenance (MTTCM), and operational availability (AO).

The RAM statistics are intended for use by EHSC for a variety of analyses, evaluations, and planning studies for C^3I facility support systems. To meet the requirements of these applications, the RAM statistics were calculated using both period hours (i.e., calendar time) and operating hours.

RESULTS

The data base developed contains more than 6000 maintenance events, representing 708 unit-years and nearly one million operating hours. Data from units within each of the six categories were combined, because units within the same category are of similar technology and utilization. The unit-level RAM statistics for the six major categories from this data base are compiled in Tables III and IV. Data for subsystems and components within these categories are presented in Appendix II.

TABLE II
DEFINITIONS OF TERMS

Concurrent Maintenance Event (CC)	Maintenance action taken while unit is already in an outage
Corrective Maintenance Event (CM)	An event in which some equipment had to be repaired (outage-causing or not)
Corrective Maintenance Time	Time, in hours, required to complete a CM
Failure	An unexpected event that results in the interruption of electrical power at the generator output terminals
Forced-Outage Event (FO)	Failure
Noncurtailing Event (NC)	Maintenance action taken while the unit is available to produce power
Operating Hours	Number of hours the unit is producing power
Outage Event	Any interruption of electrical power at the generator output terminals
Period Hours (PH)	Number of calendar hours in a year (8,760)
Planned Outage Event (PO)	Outage taken for any scheduled reason (e.g., inspections, overhauls, cleaning)
Planned Outage Time	Time, in hours, taken to complete any planned outage event
Repair Time	Time, in hours, required to repair any failure
Unit-Years	Calendar hours in a year (8,760) multiplied by the number of units

TABLE III
COMPOSITE RAM STATISTICS BASED ON PERIOD HOURS

RAM Measures	Diesel Auxiliary		Diesel Package		Gas Turbine	
	Continuous	Standby	Continuous	Standby	Continuous	Standby
Number of Units	7	5	9	15	15	20
Period Hours	674,520	1,357,800	814,776	1,068,594	333,888	1,951,224
Number of Events	1,702	1,408	1,535	498	509	319
Unit Failures	302	198	408	118	174	70
Unit Outages (Planned and Forced)	1,311	615	959	365	385	278
Number of Corrective Maintenance Events	409	630	812	243	253	102
Failure Rate (Failures per Unit-Year)	3.9	1.2	4.3	0.9	4.5	0.3
MTBF (Hours)	2,233.5	6,857.4	1,997.0	9,055.8	1,918.8	27,874.6
MTTR (Hours)	2.9	2.8	6.4	3.9	7.2	111.6
MTBPO (Hours)	668.5	3,256.1	1,478.7	4,326.2	1,582.4	9,380.8
MTTM (Hours)	1.3	3.8	12.5	7.8	21.1	10.6
MTBO (Hours)	514.5	2,207.8	849.6	2,927.7	867.2	7,018.8
MDT (Hours)	1.7	3.5	9.9	6.5	14.8	36.1
MTBCM (Hours)	1,699.1	2,155.2	923.3	4,897.5	1,319.7	19,129.6
MTTCM (Hours)	2.8	2.9	4.3	2.9	5.7	77.4
AI	0.9986	0.9995	0.9967	0.9995	0.9962	0.9959
AO	0.9965	0.9984	0.9882	0.9977	0.9828	0.9948
R24	0.9893	0.9965	0.9880	0.9973	0.9875	0.9991
R720	0.7244	0.9003	0.6973	0.9235	0.6871	0.9745

Observations

The objective of the study was to compile a data base for use in the evaluation of power systems in C^3I facilities; thus no detailed analysis of the data was performed. However, some observations can be made from examination of the calculation results.

Table III indicates that, on the basis of period hours, units in the continuous-duty categories have similar failure rates. The period-based failure rates for the standby categories are much lower, because the low utilization of units in this category provides fewer opportunities for failures to occur.

The gas turbines exhibit the lowest failure rates of units in standby service. However, this is negated by long repair times. The raw data show that the large repair-time value is attributable to a relatively small number of long-duration events, including a main bearing failure (200 h), a reduction-gear failure (350 h), seven broker starter shafts (150 h each), and two events in which the turbine had to be sent back to the manufacturer (3000 h each). The starter-shaft problem was an initial design problem and has not occurred since the implementation of a design change to the part.

For the continuous-duty diesels with auxiliary systems, the failure rate based on operating hours, shown in Table IV, is significantly higher than that of the other categories in continuous service. This difference is attributable to the relatively low utilization of these diesels at the plants reporting in this category. These units were classified as continuous because they were scheduled for operation on a regular basis. However, most of them were operated in a cycling mode and operated only for several hours each day. The high failure rate results

TABLE IV
COMPOSITE RAM STATISTICS BASED ON OPERATING HOURS

RAM Measures	Diesel Auxiliary		Diesel Package		Gas Turbine	
	Continuous	Standby	Continuous	Standby	Continuous	Standby
Number of Units	7	5	9	15	15	20
Operating Hours	80,174	323,242	300,698	64,364	204,037	13,591
Number of Events	1,702	1,408	1,535	498	509	319
Unit Failures	302	198	408	118	174	70
Unit Outages (Planned and Forced)	1,311	615	959	365	385	278
Number of Corrective Maintenance Events	409	630	872	243	253	102
Failure Rate (Failures per Unit-Year)	32.9	5.3	11.8	16.0	7.4	45.1
MTBF (Hours)	264.4	1,632.5	737.0	545.4	1,172.6	194.1
MTTR (Hours)	2.9	2.8	6.4	3.9	7.2	111.6
MTBPO (Hours)	79.4	775.1	545.7	260.5	967.0	65.3
MTTM (Hours)	1.3	3.8	12.5	7.8	21.1	10.6
MTBO (Hours)	61.1	525.5	313.5	176.3	529.9	48.8
MDT (Hours)	1.7	3.5	9.9	6.5	14.8	36.1
MTBCM (Hours)	196.0	513.0	344.8	264.8	806.4	133.2
MTTCM (Hours)	2.8	2.9	4.3	2.9	5.7	77.4
AI	0.9889	N/A	0.9912	N/A	0.9938	N/A
AO	0.9713	N/A	0.9682	N/A	0.9720	N/A
R24	0.9132	0.9854	0.9680	0.9569	0.9797	0.8837
R720	0.0657	0.6434	0.3765	0.2671	0.5412	0.0245

from dividing the large number of failures induced in this type of operation by the relatively small number of operating hours.

Similarly, for the gas turbines in standby service, the high failure rate based on operating hours can be attributed to the relatively low utilization of these units. Most of the units in this category are used as emergency power supplies in computer or communications facilities. They are typically tested on a weekly or monthly basis and run for less than 1 h, with failures most likely to occur during the start sequence. On the basis of this limited operating time, the failure rate is high.

The subsystem and component data presented in Appendix II provide information on the causes of unit failures and unavailability. For example, problems with the standby gas turbines reside mostly in the starting system, particularly the battery. The fuel system, the generator, and the controls add to the overall failure rate. It is also of interest that much of the unavailability is due to inspection and cleaning actions, even though these actions do not contribute to the overall failure rate. For the continuous-duty auxiliary diesels, the failure rate is due largely to the engine itself, specifically the cylinder heads and the crankcase. Tracking these same components through all of the diesel categories shows them to have consistently the highest failure rate.

SUMMARY

Information collected through this study is useful in the design assessment of primary and standby power systems for military or commercial facilities. The unit-level RAM statistics for the six categories provide a baseline for comparison of RAM measures for a specific plant against a representative population similar in configuration and type of service. The subsystem and component data, in conjunction with appropriate modeling tools, provide a means for forecasting the availability performance of specific plant designs. Since the data base includes all component maintenance events rather than just outage failures, it provides information that will be useful in maintenance and logistic planning for power systems.

TABLE V
ACTION, FAILURE-IMPACT, AND OUTAGE-TYPE CODES

Action Codes		
CL	—	Cleaned
FL	—	Fixed Leak
IN	—	Inspection
MD	—	Modification
NA	—	No Action Taken
OV	—	Overhaul
PM	—	Preventive Maintenance
RA	—	Repaired
RC	—	Recalibrated
TS	—	Tested
Failure Impact		
0	—	No Failure
1	—	Failure Affected Only the Component
2	—	Failure Affected Component and Subsystem
3	—	Failure Affected Component, Subsystem, and Unit
Outage Type		
CC	—	Concurrent Maintenance
FO	—	Forced Outage
FS	—	Failure to Start
NC	—	Noncurtailing Maintenance
PO	—	Planned Outage

APPENDIX I

CODES

Failure-impact, outage-type, and the action codes are listed in Table V.

APPENDIX II

SUBSYSTEM AND COMPONENT DATA

Tables VI–XI reflect the RAM statistics based on equipment failure maintenance events for the units within the six categories. Components or subsystems that do not appear in a table did not experience any failure or maintenance events.

TABLE VI
Subsystem and Component RAM Measures for Continuous-Duty Auxiliary Diesels

Equipment	Period Hours					Operating Hours			
	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)	Operational Availability	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)
CONTROL & INSTRUMENTATION (DS–CTI)	0.08	112420.0	112420.0	1.7	1.0000	0.66	13362.3	13362.3	1.7
CIRCUIT BREAKERS (DS–CTI01)	0.05	168630.0	168630.0	1.5	1.0000	0.44	20043.5	20043.5	1.5
ELECTRICAL MODULE (DS–CTI02)	0.01	674520.0	674520.0	1.0	1.0000	0.11	80174.0	80174.0	1.0
SWITCHES (DS–CTI04)	0.01	674520.0	674520.0	3.0	1.0000	0.11	80174.0	80174.0	3.0
COOLING WATER SYSTEM (DS–CWT)	0.13	67452.0	44968.0	1.7	1.0000	1.09	8017.4	5344.9	1.7
COOLING WATER PUMP (DS–CWT02)	0.00	0.0	674520.0	0.5	1.0000	0.00	0.0	80174.0	0.5
ENGINE COOLING (DS–CWT03)	0.01	674520.0	674520.0	4.0	1.0000	0.11	80174.0	80174.0	4.0
THERMOSTAT (DS–CWT05)	0.00	0.0	674520.0	1.0	1.0000	0.00	0.0	80174.0	1.0
VALVES (DS–CWT07)	0.01	674520.0	337260.0	0.8	1.0000	0.11	80174.0	40087.0	0.8
WATER LINE (DS–CWT09)	0.06	134904.0	96360.0	0.9	1.0000	0.55	16034.8	11453.4	0.9
HEAT EXCHANGER (DS–CWT10)	0.03	337260.0	337260.0	5.0	1.0000	0.22	40087.0	40087.0	5.0
WATER HEADER (DS–CWT12)	0.01	674520.0	674520.0	2.0	1.0000	0.11	80174.0	80174.0	2.0
WATER MANIFOLD (DS–CWT13)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
DIESEL ENGINE (DS–ENG)	2.25	3899.0	3122.8	3.6	0.9984	18.90	463.4	371.2	3.6
BEARINGS (DS–ENG01)	0.08	112420.0	74946.7	2.9	0.9999	0.66	13362.3	8908.2	2.9
CYLINDER (DS–ENG02)	0.32	26980.8	20440.0	2.0	0.9999	2.73	3207.0	2429.5	2.0
CYLINDER HEADS (DS–ENG03)	0.99	8875.3	8225.9	4.0	0.9995	8.30	1054.9	977.7	4.0
DRIVE SHAFT (DS–ENG04)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
PISTONS (DS–ENG06)	0.26	33726.0	28105.0	4.7	0.9998	2.19	4008.7	3340.6	4.7
TURBO CHARGER (DS–ENG07)	0.01	674520.0	337260.0	4.0	1.0000	0.11	80174.0	40087.0	4.0
VALVES (DS–ENG08)	0.03	337260.0	224840.0	2.0	1.0000	0.22	40087.0	26724.7	2.0
RINGS (DS–ENG09)	0.31	28105.0	18230.3	3.5	0.9996	2.62	3340.6	2166.9	3.5
TIMING (DS–ENG10)	0.05	168630.0	134904.0	1.0	0.9998	0.44	20043.5	16034.8	1.0
INTAKE MANIFOLD (DS–ENG11)	0.08	112420.0	112420.0	3.2	1.0000	0.66	13362.3	13362.3	3.2
CRANKCASE (DS–ENG12)	0.01	674520.0	224840.0	15.0	0.9999	0.11	80174.0	26724.7	15.0
RODS (DS–ENG14)	0.01	674520.0	224840.0	3.7	1.0000	0.11	80174.0	26724.7	3.7
CAM (DS–ENG15)	0.08	112420.0	96360.0	2.0	0.9999	0.66	13362.3	11453.4	2.0
CHAIN DRIVE (DS–ENG17)	0.01	674520.0	337260.0	1.0	1.0000	0.11	80174.0	40087.0	1.0
TAPPET (DS–ENG18)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
EXHAUST SYSTEM (DS–EXH)	0.04	224840.0	96360.0	2.1	0.9997	0.33	26724.7	11453.4	2.1
EXHAUST SYSTEM (DS–EXH)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
EXPANSION JOINTS (DS–EXH03)	0.00	0.0	337260.0	4.0	1.0000	0.00	0.0	40087.0	4.0
PORTS (DS–EXH05)	0.01	674520.0	674520.0	0.5	0.9997	0.11	80174.0	80174.0	0.5
EXHAUST MANIFOLD (DS–EXH06)	0.03	337260.0	337260.0	0.5	1.0000	0.22	40087.0	40087.0	0.5
EXHAUST VALVE (DS–EXH07)	0.00	0.0	674520.0	1.0	1.0000	0.00	0.0	80174.0	1.0
MUFFLER (DS–EXH10)	0.00	0.0	674520.0	4.0	1.0000	0.00	0.0	80174.0	4.0
FUEL SYSTEM (DS–FLS)	0.91	9636.0	8225.9	2.1	0.9989	7.65	1145.3	977.7	2.1
DEAERATOR TANK (DS–FLS02)	0.00	0.0	674520.0	1.0	1.0000	0.00	0.0	80174.0	1.0
FUEL FILTER (DS–FLS03)	0.00	0.0	337260.0	1.0	1.0000	0.00	0.0	40087.0	1.0
GOVERNOR (DS–FLS04)	0.12	74946.7	67452.0	3.2	0.9997	0.98	8908.2	8017.4	3.2
PUMPS (DS–FLS06)	0.35	24982.2	21758.7	1.8	0.9999	2.95	2969.4	2586.3	1.8
VALVES (DS–FLS07)	0.01	674520.0	674520.0	1.5	1.0000	0.11	80174.0	80174.0	1.5
INJECTOR (DS–FLS08)	0.21	42157.5	39677.6	2.5	0.9994	1.75	5010.9	4716.1	2.5
FUEL LINE (DS–FLS09)	0.22	39677.6	37473.3	1.8	1.0000	1.86	4716.1	4454.1	1.8
FUEL OIL REGULATOR (DS–FLS10)	0.00	0.0	337260.0	2.0	1.0000	0.00	0.0	40087.0	2.0
GENERATOR (DS–GNR)	0.09	96360.0	74946.7	2.2	0.9999	0.76	11453.4	8908.2	2.2
GENERATOR (DS–GNR)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
BEARINGS (DS–GNR01)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
FIELD (DS–GNR05)	0.05	168630.0	112420.0	1.8	1.0000	0.44	20043.5	13362.3	1.8
FLYWHEEL (DS–GNR10)	0.04	224840.0	224840.0	3.0	1.0000	0.33	26724.7	26724.7	3.0
INSULATION (DS–GNR11)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
COLLECTOR RINGS (DS–GNR12)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
LUBE OIL/HYDRAULIC SYSTEM (DS–LBO)	0.25	35501.1	19272.0	2.5	0.9998	2.08	4219.7	2290.7	2.5
LUBE OIL/HYDRAULIC SYSTEM (DS–LBO)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
COOLER (DS–LBO02)	0.16	56210.0	56210.0	3.8	0.9999	1.31	6681.2	6681.2	3.8
FILTER (DS–LBO04)	0.00	0.0	74946.7	0.8	1.0000	0.00	0.0	8908.2	0.8
PIPING (DS–LBO06)	0.01	674520.0	337260.0	2.0	1.0000	0.11	80174.0	40087.0	2.0
STRAINER (DS–LBO10)	0.01	674520.0	134904.0	1.4	1.0000	0.11	80174.0	16034.8	1.4
LUBRICATOR (DS–LBO12)	0.06	134904.0	96360.0	3.3	1.0000	0.55	6034.8	11453.4	3.3
STARTING SYSTEM (DS–STS)	0.18	48180.0	17295.4	1.6	0.9999	1.53	5726.7	2055.7	1.6
AIR FILTER (DS–STS04)	0.00	0.0	26980.8	1.4	1.0000	0.00	0.0	3207.0	1.4
AIR CYLINDER (DS–STS05)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
STARTING AIR ELBOW (DS–STS06)	0.13	67452.0	67452.0	2.2	1.0000	1.09	8017.4	8017.4	2.2
AIR LINE (DS–STS07)	0.03	337260.0	337260.0	1.0	1.0000	0.22	40087.0	40087.0	1.0
VALVES (DS–STS08)	0.03	337260.0	337260.0	2.5	1.0000	0.22	40087.0	40087.0	2.5
GOVERNOR BOOSTER (DS–STS13)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0

TABLE VII
SUBSYSTEM AND COMPONENT RAM MEASURES FOR STABILITY AUXILIARY DIESELS

Equipment	Period Hours					Operating Hours			
	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)	Operational Availability	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)
CONTROL & INSTRUMENTATION (DS-CTI)	0.01	678900.0	452600.0	1.7	1.0000	0.05	161621.0	107747.3	1.7
CIRCUIT BREAKERS (DS-CTI01)	0.01	1357800.0	1357800.0	2.0	1.0000	0.03	323242.0	323242.0	2.0
GAUGES (DS-CTI03)	0.01	1357800.0	678900.0	1.5	1.0000	0.03	323242.0	161621.0	1.5
SWITCHES (DS-CTI04)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
COOLING WATER SYSTEM (DS-CWT)	0.05	193971.4	135780.0	1.8	1.0000	0.19	46177.4	32324.2	1.8
AIR COOLER (DS-CWT01)	0.01	1357800.0	1357800.0	1.0	1.0000	0.03	323242.0	323242.0	1.0
COOLING WATER PUMP (DS-CWT02)	0.01	678900.0	271560.0	1.8	1.0000	0.05	161621.0	64648.4	1.8
COOLING TOWERS (DS-CWT08)	0.01	1357800.0	1357800.0	2.0	1.0000	0.03	323242.0	323242.0	2.0
HEAT EXCHANGER (DS-CWT10)	0.02	452600.0	452600.0	1.8	1.0000	0.08	107747.3	107747.3	1.8
DIESEL ENGINE (DS-ENG)	0.64	13715.2	4437.3	3.8	0.9988	2.68	3265.1	1056.3	3.8
DIESEL ENGINE (DS-ENG)	0.01	1357800.0	1357800.0	0.0	0.9998	0.03	323242.0	323242.0	0.0
BEARINGS (DS-ENG01)	0.10	84862.5	38794.3	2.4	1.0000	0.43	20202.6	9235.5	2.4
CYLINDER (DS-ENG02)	0.05	193971.4	150866.7	2.8	1.0000	0.19	46177.4	35915.8	2.8
CYLINDER HEADS (DS-ENG03)	0.12	71463.2	52223.1	3.4	0.9999	0.51	17012.7	12432.4	3.4
PISTONS (DS-ENG06)	0.19	45260.0	9236.7	4.4	0.9992	0.81	10774.7	2198.9	4.4
VALVES (DS-ENG08)	0.01	1357800.0	271560.0	2.5	1.0000	0.03	323242.0	64648.4	2.5
RINGS (DS-ENG09)	0.15	59034.8	16972.5	3.6	0.9999	0.62	14054.0	4040.5	3.6
INTAKE MANIFOLD (DS-ENG11)	0.01	1357800.0	1357800.0	2.0	1.0000	0.03	323242.0	323242.0	2.0
CRANKCASE (DS-ENG12)	0.00	0.0	1357800.0	4.0	1.0000	0.00	0.0	323242.0	4.0
CAM (DS-ENG15)	0.01	1357800.0	1357800.0	8.0	1.0000	0.03	323242.0	323242.0	8.0
EXHAUST SYSTEM (DS-EXH)	0.03	339450.0	79870.6	1.9	0.9999	0.11	80810.5	19014.2	1.9
EXHAUST SYSTEM (DS-EXH)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
EXHAUST MANIFOLD (DS-EXH06)	0.00	0.0	1357800.0	2.0	1.0000	0.00	0.0	323242.0	2.0
EXHAUST VALVE (DS-EXH07)	0.02	52600.0	90520.0	1.9	1.0000	0.08	107747.3	21549.5	1.9
HEADER (DS-EXH09)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
MUFFLER (DS-EXH10)	0.01	1357800.0	1357800.0	1.5	1.0000	0.03	323242.0	323242.0	1.5
FUEL SYSTEM (DS-FLS)	0.41	21552.4	7339.5	2.7	0.9998	1.71	5130.8	1747.3	2.7
FUEL SYSTEM (DS-FLS)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
FUEL FILTER (DS-FLS03)	0.02	452600.0	21552.4	1.1	1.0000	0.08	107747.3	5130.8	1.1
GOVERNOR (DS-FLS04)	0.05	193971.4	169725.0	3.0	1.0000	0.19	6177.4	40405.2	3.0
PUMPS (DS-FLS06)	0.06	135780.0	113150.0	2.2	1.0000	0.27	32324.2	26936.8	2.2
INJECTOR (DS-FLS08)	0.25	35731.6	13997.9	3.7	0.9999	1.03	8506.4	3332.4	3.7
FUEL LINE (DS-FLS09)	0.03	271560.0	271560.0	2.6	1.0000	0.14	64648.4	64648.4	2.6
FUEL OIL REGULATOR (DS-FLS10)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
GENERATOR (DS-GNR)	0.06	135780.0	123436.4	2.3	1.0000	0.27	32324.2	29385.6	2.3
GENERATOR (DS-GNR)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
BEARINGS (DS-GNR01)	0.02	452600.0	339450.0	2.2	1.0000	0.08	107747.3	80810.5	2.2
FIELD (DS-GNR05)	0.04	226300.0	226300.0	2.2	1.0000	0.16	53873.7	53873.7	2.2
COLLECTOR RINGS (DS-GNR12)	0.01	1357800.0	1357800.0	3.0	1.0000	0.03	323242.0	323242.0	3.0
LUBE OIL/HYDRAULIC SYSTEM (DS-LBO)	0.06	135780.0	64657.1	1.2	0.9999	0.27	32324.2	15392.5	1.2
LUBE OIL/HYDRAULIC SYSTEM (DS-LBO)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
COOLER (DS-LBO02)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
FILTER (DS-LBO04)	0.01	1357800.0	113150.0	0.9	1.0000	0.03	323242.0	26936.8	0.9
PUMP (DS-LBO05)	0.05	193971.4	193971.4	1.6	1.0000	0.19	6177.4	46177.4	1.6
TANK (DS-LBO08)	0.01	1357800.0	1357800.0	2.0	1.0000	0.03	323242.0	323242.0	2.0
STRAINER (DS-LBO10)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
OIL SWITCH (DS-LBO14)	0.01	1357800.0	1357800.0	1.0	1.0000	0.03	323242.0	323242.0	1.0
STARTING SYSTEM (DS-STS)	0.02	452600.0	17407.7	1.0	1.0000	0.08	107747.3	4144.1	1.0
AIR FILTER (DS-STS04)	0.00	0.0	18104.0	1.0	1.0000	0.00	0.0	4309.9	1.0
VALVES (DS-STS08)	0.02	452600.0	452600.0	1.7	1.0000	0.08	107747.3	107747.3	1.7

TABLE VIII
SUBSYSTEM AND COMPONENT RAM MEASURES FOR CONTINUOUS-DUTY PACKAGE DIESELS

Equipment	Period Hours: Failures per Year	Period Hours: MTBF (Hours)	Period Hours: MTBCM (Hours)	Period Hours: MTTCM (Hours)	Period Hours: Operational Availability	Operating Hours: Failures per Year	Operating Hours: MTBF (Hours)	Operating Hours: MTBCM (Hours)	Operating Hours: MTTCM (Hours)
BALANCE OF PLANT (DS-BOP)	0.02	407388.0	271592.0	0.3	1.0000	0.06	150349.0	100232.7	0.3
BALANCE OF PLANT (DS-BOP)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
COMBUSTION GAS MONITORING (DS-BOP01)	0.01	814776.0	814776.0	0.0	1.0000	0.03	300698.0	300698.0	0.0
ENCLOSURES (DS-BOP02)	0.00	0.0	814776.0	1.0	1.0000	0.00	0.0	300698.0	1.0
FIRE SUPPRESSION/DETECTION (DS-BOP03)	0.01	814776.0	814776.0	0.0	1.0000	0.03	300698.0	300698.0	0.0
CONTROL & INSTRUMENTATION (DS-CTI)	0.12	74070.5	28095.7	3.0	0.9999	0.32	27336.2	10368.9	3.0
CONTROL & INSTRUMENTATION (DS-CTI)	0.00	0.0	407388.0	1.5	1.0000	0.00	0.0	150349.0	1.5
CIRCUIT BREAKERS (DS-CTI01)	0.00	0.0	814776.0	1.0	1.0000	0.00	0.0	300698.0	1.0
ELECTRICAL MODULE (DS-CTI02)	0.04	203694.0	162955.2	4.5	1.0000	0.12	75174.5	60139.6	4.5
GAUGES (DS-CTI03)	0.04	203694.0	47928.0	1.2	1.0000	0.12	75174.5	17688.1	1.2
SWITCHES (DS-CTI04)	0.01	814776.0	407388.0	5.7	1.0000	0.03	300698.0	150349.0	5.7
WIRING (DS-CTI05)	0.02	407388.0	407388.0	14.0	1.0000	0.06	150349.0	150349.0	14.0
COOLING WATER SYSTEM (DS-CWT)	0.43	20369.4	10720.7	1.6	0.9998	1.17	7517.4	3956.6	1.6
COOLING WATER SYSTEM (DS-CWT)	0.01	814776.0	814776.0	5.6	1.0000	0.03	300698.0	300698.0	5.6
COOLING WATER PUMP (DS-CWT02)	0.13	67898.0	37035.3	2.2	0.9999	0.35	25058.2	13668.1	2.2
ENGINE COOLING (DS-CWT03)	0.22	40738.8	23964.0	1.2	0.9999	0.58	15034.9	8844.1	1.2
THERMOSTAT (DS-CWT05)	0.01	814776.0	162955.2	1.3	1.0000	0.03	300698.0	60139.6	1.3
TURBO CHARGER COOLING (DS-CWT06)	0.00	0.0	814776.0	2.0	1.0000	0.00	0.0	300698.0	2.0
VALVES (DS-CWT07)	0.01	814776.0	407388.0	1.5	1.0000	0.03	300698.0	150349.0	1.5
COOLING TOWERS (DS-CWT08)	0.01	814776.0	407388.0	1.0	1.0000	0.03	300698.0	150349.0	1.0
WATER LINE (DS-CWT09)	0.02	407388.0	135796.0	2.1	1.0000	0.06	150349.0	50116.3	2.1
HEAT EXCHANGER (DS-CWT10)	0.01	814776.0	814776.0	1.0	1.0000	0.03	300698.0	300698.0	1.0
WATER HEADER (DS-CWT12)	0.00	0.0	814776.0	2.0	1.0000	0.00	0.0	300698.0	2.0
WATER MANIFOLD (DS-CWT13)	0.01	814776.0	814776.0	1.0	1.0000	0.03	300698.0	300698.0	1.0
DIESEL ENGINE (DS-ENG)	1.91	4577.4	3409.1	8.5	0.9902	5.19	1689.3	1258.2	8.5
DIESEL ENGINE (DS-ENG)	0.04	203694.0	135796.0	9.7	0.9950	0.12	75174.5	50116.3	9.7
BEARINGS (DS-ENG01)	0.09	101847.0	81477.6	8.9	0.9999	0.23	37587.2	30069.8	8.9
CYLINDER (DS-ENG02)	0.30	29099.1	19399.4	4.3	0.9999	0.82	10739.2	7159.5	4.3
CYLINDER HEADS (DS-ENG03)	0.77	11316.3	10445.8	10.7	0.9968	2.10	4176.4	3855.1	10.7
DRIVE SHAFT (DS-ENG04)	0.02	407388.0	271592.0	30.0	0.9999	0.06	150349.0	100232.7	30.0
PISTONS (DS-ENG06)	0.22	40738.8	32591.0	2.9	0.9999	0.58	15034.9	12027.9	2.9
TURBO CHARGER (DS-ENG07)	0.14	62675.1	35425.0	3.6	0.9995	0.38	23130.6	13073.8	3.6
VALVES (DS-ENG08)	0.02	407388.0	203694.0	3.8	1.0000	0.06	150349.0	75174.5	3.8
RINGS (DS-ENG09)	0.04	203694.0	81477.6	8.3	1.0000	0.12	75174.5	30069.8	8.3
TIMING (DS-ENG10)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
INTAKE MANIFOLD (DS-ENG11)	0.05	162955.2	135796.0	9.9	0.9999	0.15	60139.6	50116.3	9.9
CRANKCASE (DS-ENG12)	0.10	90530.7	90530.7	5.6	0.9998	0.26	33410.9	33410.9	15.6
RODS (DS-ENG14)	0.02	407388.0	407388.0	21.5	0.9999	0.06	50349.0	150349.0	21.5
CAM (DS-ENG15)	0.08	116396.6	58198.3	14.1	0.9998	0.20	42956.9	21478.4	14.1
CHAIN DRIVE (DS-ENG17)	0.01	814776.0	407388.0	21.0	1.0000	0.03	300698.0	150349.0	21.0
TAPPET (DS-ENG18)	0.01	814776.0	162955.2	9.7	1.0000	0.03	300698.0	60139.6	9.7
EXHAUST SYSTEM (DS-EXH)	0.12	74070.5	40738.8	5.2	0.9997	0.32	27336.2	15034.9	5.2
EXHAUST SYSTEM (DS-EXH)	0.01	814776.0	407388.0	5.0	0.9998	0.03	300698.0	150349.0	5.0
EXHAUST DUCTING (DS-EXH01)	0.00	0.0	814776.0	2.0	1.0000	0.00	0.0	300698.0	2.0
EXPANSION JOINTS (DS-EXH03)	0.01	814776.0	203694.0	2.9	1.0000	0.03	300698.0	75174.5	2.9
EXHAUST MANIFOLD (DS-EXH06)	0.06	135796.0	116396.6	9.2	0.9999	0.17	50116.3	42956.9	9.2
EXHAUST VALVE (DS-EXH07)	0.03	271592.0	135796.0	2.8	1.0000	0.09	100232.7	50116.3	2.8
MUFFLER (DS-EXH10)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0

TABLE VIII (Continued)

Equipment	Period Hours: Failures per Year	Period Hours: MTBF (Hours)	Period Hours: MTBCM (Hours)	Period Hours: MTTCM (Hours)	Period Hours: Operational Availability	Operating Hours: Failures per Year	Operating Hours: MTBF (Hours)	Operating Hours: MTBCM (Hours)	Operating Hours: MTTCM (Hours)
FUEL SYSTEM (DS-FLS)	1.19	7340.3	3366.8	3.5	0.9992	3.23	2709.0	1242.6	3.5
FUEL SYSTEM (DS-FLS)	0.01	814776.0	814776.0	1.0	1.0000	0.03	300698.0	300698.0	1.0
DAY TANKS (DS-FLS01)	0.01	814776.0	203694.0	1.5	1.0000	0.03	300698.0	75174.5	1.5
FUEL FILTER (DS-FLS03)	0.02	407388.0	12730.9	1.2	1.0000	0.06	150349.0	4698.4	1.2
GOVERNOR (DS-FLS04)	0.27	32591.0	23279.3	5.5	0.9997	0.73	12027.9	8591.4	5.5
PUMPS (DS-FLS06)	0.24	37035.3	23279.3	3.3	0.9999	0.64	13668.1	8591.4	3.3
VALVES (DS-FLS07)	0.06	135796.0	101847.0	2.1	1.0000	0.17	50116.3	37587.2	2.1
INJECTOR (DS-FLS08)	0.40	22021.0	13357.0	6.0	0.9998	1.08	8127.0	4929.5	6.0
FUEL LINE (DS-FLS09)	0.18	47928.0	23964.0	2.1	0.9999	0.50	17688.1	8844.1	2.1
GEARBOX (DS-GBX)	0.01	814776.0	814776.0	12.0	1.0000	0.03	300698.0	300698.0	12.0
GEARBOX (DS-GBX)	0.01	814776.0	814776.0	12.0	1.0000	0.03	300698.0	300698.0	12.0
GENERATOR (DS-GNR)	0.09	101847.0	74070.5	7.7	0.9999	0.23	37587.2	27336.2	7.7
GENERATOR (DS-GNR)	0.04	203694.0	203694.0	18.9	0.9999	0.12	75174.5	75174.5	18.9
COOLING FANS (DS-GNR04)	0.00	0.0	0.0	10.0	1.0000	0.00	0.0	0.0	0.0
FIELD (DS-GNR05)	0.03	271592.0	203694.0	1.0	1.0000	0.09	100232.7	75174.5	1.0
FLYWHEEL (DS-GNR10)	0.01	814776.0	271592.0	1.8	1.0000	0.03	300698.0	100232.7	1.8
LUBE OIL/HYDRAULIC SYSTEM (DS-LBO)	0.30	29099.1	5580.7	2.0	0.9997	0.82	10739.2	2059.6	2.0
LUBE OIL/HYDRAULIC SYSTEM (DS-LBO)	0.00	0.0	814776.0	4.0	1.0000	0.00	0.0	300696.0	4.0
HEATER (DS-LBO01)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
COOLER (DS-LBO02)	0.01	814776.0	814776.0	74.2	0.9999	0.03	300698.0	300698.0	74.2
COOLER FAN (DS-LBO03)	0.01	814776.0	814776.0	2.0	1.0000	0.03	300698.0	300698.0	2.0
FILTER (DS-LBO04)	0.02	407388.0	8761.0	1.2	1.0000	0.06	150349.0	3233.3	1.2
PUMP (DS-LBO05)	0.12	74070.5	42882.9	1.7	0.9999	0.32	27336.2	15826.2	1.7
PIPING (DS-LBO06)	0.10	90530.7	40738.8	2.4	1.0000	0.26	33410.9	15034.9	2.4
TANK (DS-LBO08)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
VALVES (DS-LBO09)	0.02	407388.0	135796.0	1.5	1.0000	0.06	150349.0	50116.3	1.5
STRAINER (DS-LBO10)	0.02	407388.0	203694.0	1.2	1.0000	0.06	150349.0	75174.5	1.2
OIL SWITCH (DS-LBO14)	0.00	0.0	814776.0	1.0	1.0000	0.00	0.0	300698.0	1.0
STARTING SYSTEM (DS-STS)	0.19	45265.3	7686.6	1.6	0.9999	0.52	16705.4	2836.8	1.6
STARTING SYSTEM (DS-STS)	0.00	0.0	814776.0	2.5	1.0000	0.00	0.0	300698.0	2.5
STARTING AIR COMPRESSOR (DS-STS02)	0.03	271592.0	271592.0	4.2	1.0000	0.09	100232.7	100232.7	4.2
AIR FILTER (DS-STS04)	0.00	0.0	10720.7	1.3	1.0000	0.00	0.0	3956.6	1.3
STARTING AIR ELBOW (DS-STS06)	0.01	814776.0	814776.0	1.0	1.0000	0.03	300698.0	300698.0	1.0
AIR LINE (DS-STS07)	0.01	814776.0	814776.0	1.0	1.0000	0.03	300698.0	300698.0	1.0
VALVES (DS-STS08)	0.01	814776.0	407388.0	1.2	1.0000	0.03	300698.0	150349.0	1.2
AIR STARTS (DS-STS10)	0.12	74070.5	42882.9	2.5	1.0000	0.32	27336.2	15826.2	2.5
AIR INTAKE (DS-STS11)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
AIR DISTRIBUTOR (DS-STS12)	0.01	814776.0	814776.0	1.5	1.0000	0.03	300698.0	300698.0	1.5
BATTERY (DS-STS15)	0.00	0.0	407388.0	1.2	1.0000	0.00	0.0	150349.0	1.2

TABLE IX
SUBSYSTEM AND COMPONENT RAM MEASURES FOR STANDBY PACKAGE DIESELS

Equipment	Period Hours					Operating Hours			
	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)	Operational Availability	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)
CONTROL & INSTRUMENTATION (DS-CTI)	0.05	178099.0	152656.3	1.2	1.0000	0.82	10727.3	9194.9	1.2
CIRCUIT BREAKERS (DS-CTI01)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
GAUGES (DS-CTI03)	0.04	213718.8	178099.0	1.2	1.0000	0.68	12872.8	10727.3	1.2
THERMOCOUPLES (DS-CTI06)	0.01	1068594.0	1068594.0	1.0	1.0000	0.14	64364.0	64364.0	1.0
COOLING WATER SYSTEM (DS-CWT)	0.07	133574.2	56241.8	1.9	1.0000	1.09	8045.5	3387.6	1.9
COOLING WATER PUMP (DS-CWT02)	0.04	213718.8	89049.5	1.8	1.0000	0.68	12872.8	5363.7	1.8
ENGINE COOLING (DS-CWT03)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
VALVES (DS-CWT07)	0.00	0.0	1068594.0	1.0	1.0000	0.00	0.0	64364.0	1.0
COOLING TOWERS (DS-CWT08)	0.01	1068594.0	1068594.0	2.0	1.0000	0.14	64364.0	64364.0	2.0
WATER LINE (DS-CWT09)	0.01	1068594.0	534297.0	1.0	1.0000	0.14	64364.0	32182.0	1.0
HEAT EXCHANGER (DS-CWT10)	0.01	1068594.0	534297.0	5.0	1.0000	0.14	64364.0	32182.0	5.0
WATER HEADER (DS-CWT12)	0.00	0.0	1068594.0	1.0	1.0000	0.00	0.0	64364.0	1.0
DIESEL ENGINE (DS-ENG)	0.26	33393.6	18424.0	4.1	0.9995	4.36	2011.4	1109.7	4.1
DIESEL ENGINE (DS-ENG)	0.00	0.0	0.0	0.0	0.9997	0.00	0.0	0.0	0.0
BEARINGS (DS-ENG01)	0.01	1068594.0	213718.8	2.0	1.0000	0.14	64364.0	12872.8	2.0
CYLINDER (DS-ENG02)	0.05	178099.0	152656.3	2.3	1.0000	0.82	10727.3	9194.9	2.3
CYLINDER HEADS (DS-ENG03)	0.08	106859.4	62858.5	5.6	0.9999	1.36	6436.4	3786.1	5.6
PISTONS (DS-ENG06)	0.02	356198.0	178099.0	4.0	1.0000	0.41	21454.7	10727.3	4.0
TURBO CHARGER (DS-ENG07)	0.01	1068594.0	534297.0	6.0	1.0000	0.14	64364.0	32182.0	6.0
VALVES (DS-ENG08)	0.01	1068594.0	534297.0	3.0	1.0000	0.14	64364.0	32182.0	3.0
RINGS (DS-ENG09)	0.07	133574.2	97144.9	5.4	1.0000	1.09	8045.5	5851.3	5.4
TIMING (DS-ENG10)	0.00	0.0	1068594.0	1.0	1.0000	0.00	0.0	64364.0	1.0
INTAKE MANIFOLD (DS-ENG11)	0.00	0.0	534297.0	1.0	1.0000	0.00	0.0	32182.0	1.0
CRANKCASE (DS-ENG12)	0.01	1068594.0	356198.0	1.3	1.0000	0.14	64364.0	21454.7	1.3
RODS (DS-ENG14)	0.00	0.0	1068594.0	2.0	1.0000	0.00	0.0	64364.0	2.0
CAM (DS-ENG15)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
CHAIN DRIVE (DS-ENG17)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
TAPPET (DS-ENG18)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
ENGINE SWITCH GEAR (DS-ENG19)	0.01	1068594.0	1068594.0	5.0	1.0000	0.14	64364.0	64364.0	5.0
EXHAUST SYSTEM (DS-EXH)	0.02	356198.0	213718.8	1.8	1.0000	0.41	21454.7	12872.8	1.8
EXHAUST SYSTEM (DS-EXH)	0.02	534297.0	356198.0	1.7	1.0000	0.27	32182.0	21454.7	1.7
EXPANSION JOINTS (DS-EXH03)	0.01	1068594.0	1068594.0	3.0	1.0000	0.14	64364.0	64364.0	3.0
PORTS (DS-EXH05)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
EXHAUST MANIFOLD (DS-EXH06)	0.00	0.0	1068594.0	1.0	1.0000	0.00	0.0	64364.0	1.0
FUEL SYSTEM (DS-FLS)	0.24	36848.1	14841.6	2.3	0.9998	3.95	2219.4	893.9	2.3
FUEL SYSTEM (DS-FLS)	0.01	1068594.0	534297.0	1.0	1.0000	0.14	64364.0	32182.0	1.0
DAY TANKS (DS-FLS01)	0.01	1068594.0	1068594.0	1.0	1.0000	0.14	64364.0	64364.0	1.0
FUEL FILTER (DS-FLS03)	0.00	0.0	56241.8	1.0	1.0000	0.00	0.0	3387.6	1.0
GOVERNOR (DS-FLS04)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
PUMPS (DS-FLS06)	0.04	213718.8	178099.0	1.8	0.9999	0.68	12872.8	10727.3	1.8
VALVES (DS-FLS07)	0.03	267148.5	106859.4	2.1	1.0000	0.54	16091.0	6436.4	2.1
INJECTOR (DS-FLS08)	0.13	66787.1	38164.1	3.6	0.9999	2.18	4022.8	2298.7	3.6
FUEL LINE (DS-FLS09)	0.00	0.0	1068594.0	2.0	1.0000	0.00	0.0	64364.0	2.0
FUEL OIL REGULATOR (DS-FLS10)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
GAS JUMPER (DS-FLS11)	0.02	534297.0	213718.8	2.0	1.0000	0.27	32182.0	12872.8	2.0
GENERATOR (DS-GNR)	0.03	267148.5	213718.8	2.8	0.9987	0.54	16091.0	12872.8	2.8
GENERATOR (DS-GNR)	0.01	1068594.0	1068594.0	2.0	0.9987	0.14	64364.0	64364.0	2.0
FIELD (DS-GNR05)	0.02	356198.0	267148.5	3.0	1.0000	0.41	21454.7	16091.0	3.0
FLYWHEEL (DS-GNR10)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
LUBE OIL/HYDRAULIC SYSTEM (DS-LBO)	0.16	56241.8	20162.2	3.4	0.9998	2.59	3387.6	1214.4	3.4
LUBE OIL/HYDRAULIC SYSTEM (DS-LBO)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
HEATER (DS-LBO01)	0.05	178099.0	76328.1	1.9	1.0000	0.82	10727.3	4597.4	1.9
COOLER (DS-LBO02)	0.00	0.0	1068594.0	1.0	1.0000	0.00	0.0	64364.0	1.0
COOLER FAN (DS-LBO03)	0.01	1068594.0	1068594.0	15.0	1.0000	0.14	64364.0	64364.0	15.0
FILTER (DS-LBO04)	0.02	356198.0	56241.8	5.4	0.9999	0.41	21454.7	3387.6	5.4
PUMP (DS-LBO05)	0.02	356198.0	133574.2	1.9	1.0000	0.41	21454.7	8045.5	1.9
PIPING (DS-LBO06)	0.01	1068594.0	1068594.0	8.0	1.0000	0.14	64364.0	64364.0	8.0
TANK (DS-LBO08)	0.01	1068594.0	1068594.0	2.0	1.0000	0.14	64364.0	64364.0	2.0
VALVES (DS-LBO09)	0.01	1068594.0	1068594.0	2.0	1.0000	0.14	64364.0	64364.0	2.0
STRAINER (DS-LBO10)	0.02	534297.0	356198.0	1.7	1.0000	0.27	32182.0	21454.7	1.7
LUBRICATOR (DS-LBO12)	0.01	1068594.0	267148.5	1.2	1.0000	0.14	64364.0	16091.0	1.2
STARTING SYSTEM (DS-STS)	0.14	62858.5	44524.8	2.6	0.9999	2.31	3786.1	2681.8	2.6
STARTING SYSTEM (DS-STS)	0.02	534297.0	534297.0	2.5	1.0000	0.27	32182.0	32182.0	2.5
STARTING AIR COMPRESSOR (DS-STS02)	0.02	356198.0	356198.0	6.7	1.0000	0.41	21454.7	21454.7	6.7
AIR FILTER (DS-STS04)	0.00	0.0	1068594.0	1.0	1.0000	0.00	0.0	64364.0	1.0
VALVES (DS-STS08)	0.01	1068594.0	534297.0	3.0	1.0000	0.14	64364.0	32182.0	3.0
AIR STARTS (DS-STS10)	0.07	133574.2	89049.5	2.0	1.0000	1.09	8045.5	5363.7	2.0
AIR INTAKE (DS-STS11)	0.00	0.0	1068594.0	1.0	1.0000	0.00	0.0	64364.0	1.0
BATTERY (DS-STS15)	0.02	356198.0	356198.0	2.0	1.0000	0.41	21454.7	21454.7	2.0

TABLE X
SUBSYSTEM AND COMPONENT RAM MEASURES FOR CONTINUOUS-DUTY GAS TURBINES

Equipment	Period Hours					Operating Hours			
	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)	Operational Availability	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)
AIR INTAKE SYSTEM (GT-AIS)	0.00	0.0	47698.3	8.6	1.0000	0.00	0.0	29148.1	8.6
AIR INLET FILTER (GT-AIS01)	0.00	0.0	55648.0	2.0	1.0000	0.00	0.0	34006.2	2.0
DUCTING (GT-AIS03)	0.00	0.0	333888.0	48.0	1.0000	0.00	0.0	204037.0	48.0
BALANCE OF PLANT (GT-BOP)	0.05	166944.0	83472.0	2.3	0.9907	0.09	102018.5	51009.2	2.3
FIRE SUPPRESSION/DETECTION (GT-BOP03)	0.05	166944.0	83472.0	2.3	1.0000	0.09	102018.5	51009.2	2.3
TESTING (GT-BOP04)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
CLEANING (GT-BOP05)	0.00	0.0	0.0	0.0	0.9990	0.00	0.0	0.0	0.0
INSPECTION (GT-BOP06)	0.00	0.0	0.0	0.0	0.9918	0.00	0.0	0.0	0.0
COMBUSTION SYSTEM (GT-CMB)	0.21	41736.0	23849.1	1.5	0.9999	0.34	25504.6	14574.1	1.5
COMBUSTION SYSTEM (GT-CMB)	0.08	111296.0	111296.0	1.3	1.0000	0.13	68012.3	68012.3	1.3
FUEL NOZZLES (GT-CMB02)	0.13	66777.6	30353.5	1.6	1.0000	0.21	40807.4	18548.8	1.6
COMPRESSOR (GT-CMP)	0.10	83472.0	47698.3	1.1	1.0000	0.17	51009.2	29148.1	1.1
FLEXLINE (GT-CMP05)	0.00	0.0	333888.0	1.0	1.0000	0.00	0.0	204037.0	1.0
BLEEDVALVE (GT-CMP06)	0.10	83472.0	55648.0	1.2	1.0000	0.17	51009.2	34006.2	1.2
CONTROL & INSTRUMENTATION (GT-CTI)	0.63	13912.0	9274.7	1.2	0.9999	1.03	8501.5	5667.7	1.2
CONTROL & INSTRUMENTATION (GT-CTI)	0.03	333888.0	333888.0	1.0	1.0000	0.04	204037.0	204037.0	1.0
CIRCUIT BREAKERS (GT-CTI01)	0.05	166944.0	166944.0	1.0	1.0000	0.09	102018.5	102018.5	1.0
ELECTRICAL MODULE (GT-CTI02)	0.31	27824.0	23849.1	1.5	0.9999	0.52	17003.1	14574.1	1.5
GAUGES (GT-CTI03)	0.05	166944.0	37098.7	0.8	1.0000	0.09	102018.5	22670.8	0.8
SWITCHES (GT-CTI04)	0.16	55648.0	41736.0	1.1	1.0000	0.26	34006.2	25504.6	1.1
THERMOCOUPLE (GT-CTI07)	0.03	333888.0	166944.0	2.0	1.0000	0.04	204037.0	102018.5	2.0
EXHAUST SYSTEM (GT-EXH)	0.00	0.0	333888.0	1.0	1.0000	0.00	0.0	204037.0	1.0
EXHAUST FAN (GT-EXH03)	0.00	0.0	333888.0	1.0	1.0000	0.00	0.0	204037.0	1.0
FUEL SYSTEM (GT-FLS)	1.89	4637.3	3442.1	3.0	0.9992	3.09	2833.8	2103.5	3.0
FUEL SYSTEM (GT-FLS)	0.08	111296.0	111296.0	1.5	1.0000	0.13	68012.3	68012.3	1.5
AIR MANIFOLD (GT-FLS01)	0.00	0.0	333888.0	2.0	1.0000	0.00	0.0	204037.0	2.0
BOOST PUMP (GT-FLS02)	0.13	66777.6	66777.6	2.2	1.0000	0.21	40807.4	40807.4	2.2
FILTERS (GT-FLS04)	0.10	83472.0	55648.0	1.8	1.0000	0.17	51009.2	34006.2	1.8
GAS MANIFOLD (GT-FLS06)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
GOVERNOR (GT-FLS07)	0.60	14516.9	10770.6	5.9	0.9995	0.99	8871.2	6581.8	5.9
MAIN FUEL PUMP (GT-FLS08)	0.10	83472.0	66777.6	1.6	1.0000	0.17	51009.2	40807.4	1.6
ORIFICE (GT-FLS10)	0.03	333888.0	166944.0	2.0	1.0000	0.04	204037.0	102018.5	2.0
PRESSURE GAUGE (GT-FLS12)	0.03	333888.0	333888.0	1.0	1.0000	0.04	204037.0	204037.0	1.0
STRAINER (GT-FLS13)	0.05	166944.0	83472.0	1.2	1.0000	0.09	102018.5	51009.2	1.2
VALVES (GT-FLS14)	0.39	22259.2	16694.4	1.5	0.9999	0.64	13602.5	10201.9	1.5
PIPING (GT-FLS15)	0.18	47698.3	33388.8	2.6	0.9999	0.30	29148.1	20403.7	2.6
SEALS (GT-FLS16)	0.16	55648.0	47698.3	1.1	1.0000	0.26	34006.2	29148.1	1.1
FLOW METER (GT-FLS17)	0.03	333888.0	166944.0	1.0	1.0000	0.04	204037.0	102018.5	1.0
GEARBOX (GT-GBX)	0.03	333888.0	166944.0	1.5	1.0000	0.04	204037.0	102018.5	1.5
GEARBOX (GT-GBX)	0.00	0.0	333888.0	2.0	1.0000	0.00	0.0	204037.0	2.0
SEALS (GT-GBX04)	0.03	333888.0	333888.0	1.0	1.0000	0.04	204037.0	204037.0	1.0
GENERATOR (GT-GNR)	0.13	66777.6	41736.0	4.1	0.9999	0.21	40807.4	25504.6	4.1
GENERATOR (GT-GNR)	0.00	0.0	333888.0	8.0	1.0000	0.00	0.0	204037.0	8.0
BEARINGS (GT-GNR01)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
FIELD (GT-GNR05)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
STATOR (GT-GNR09)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
TURBINE COUPLING (GT-GNR10)	0.05	166944.0	83472.0	2.8	1.0000	0.09	102018.5	51009.2	2.8
VOLTAGE REGULATOR (GT-GNR11)	0.08	111296.0	111296.0	4.7	1.0000	0.13	68012.3	68012.3	4.7
LUBE OIL/HYDRAULIC SYSTEM (GT-LBO)	0.71	12366.2	8347.2	1.8	0.9998	1.16	7556.9	5100.9	1.8
AIR-TO-OIL COOLER (GT-LBO01)	0.13	66777.6	66777.6	2.3	0.9999	0.21	40807.4	40807.4	2.3
HYDRAULIC PUMP (GT-LBO02)	0.05	166944.0	166944.0	2.0	1.0000	0.09	102018.5	102018.5	2.0
LUBE OIL FILTER (GT-LBO03)	0.08	111296.0	30353.5	1.9	1.0000	0.13	68012.3	18548.8	1.9
OIL COOLER FAN (GT-LBO05)	0.08	111296.0	83472.0	2.0	1.0000	0.13	68012.3	51009.2	2.0
OIL MANIFOLDS (GT-LBO06)	0.03	333888.0	333888.0	1.0	1.0000	0.04	204037.0	204037.0	1.0
OIL TANK (GT-LBO07)	0.05	166944.0	166944.0	1.0	1.0000	0.09	102018.5	102018.5	1.0
PRE LUBE OIL PUMP (GT-LBO09)	0.10	83472.0	83472.0	2.6	1.0000	0.17	51009.2	51009.2	2.6
PIPING (GT-LBO12)	0.10	83472.0	55648.0	1.1	1.0000	0.17	51009.2	34006.2	1.1
SEALS (GT-LBO13)	0.03	333888.0	111296.0	1.0	1.0000	0.04	204037.0	68012.3	1.0
PRECIPITATOR (GT-LBO14)	0.05	166944.0	166944.0	2.5	1.0000	0.09	102018.5	102018.5	2.5
REDUCTION GEARBOX (GT-RGB)	0.03	333888.0	333888.0	2.0	1.0000	0.04	204037.0	204037.0	2.0
REDUCTION GEARBOX (GT-RGB)	0.03	333888.0	333888.0	2.0	1.0000	0.04	204037.0	204037.0	2.0

TABLE X (Continued)

Equipment	Period Hours					Operating Hours			
	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)	Operational Availability	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)
STARTING SYSTEM (GT-STS)	0.71	12366.2	9820.2	19.5	0.9980	1.16	7556.9	6001.1	19.5
STARTING SYSTEM (GT-STS)	0.08	111296.0	111296.0	0.7	1.0000	0.13	68012.3	68012.3	0.7
AIR PUMP (GT-STS01)	0.03	333888.0	111296.0	2.3	1.0000	0.04	204037.0	68012.3	2.3
FILTER (GT-STS02)	0.03	333888.0	333888.0	1.0	1.0000	0.04	204037.0	204037.0	1.0
REGULATOR (GT-STS03)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
BATTERY (GT-STS06)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
STARTING SHAFT (GT-STS07)	0.03	333888.0	333888.0	2.0	1.0000	0.04	204037.0	204037.0	2.0
STARTER MOTOR (GT-STS08)	0.13	66777.6	47698.3	83.6	0.9982	0.21	40807.4	29148.1	83.6
GARLOC SEAL (GT-STS11)	0.42	20868.0	17573.1	3.5	0.9998	0.69	12752.3	10738.8	3.5
TURBINE (GT-TRB)	0.08	111296.0	166944.0	121.0	0.9954	0.13	68012.3	102018.5	121.0
TURBINE (GT-TRB)	0.05	166944.0	333888.0	240.0	0.9954	0.09	102018.5	204037.0	240.0
CASING (GT-TRB02)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
BEARING (GT-TRB05)	0.03	333888.0	333888.0	2.0	1.0000	0.04	204037.0	204037.0	2.0

TABLE XI
SUBSYSTEM AND COMPONENT RAM MEASURES FOR STANDBY GAS TURBINES

Equipment	Period Hours					Operating Hours			
	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)	Operational Availability	Failures per Year	MTBF (Hours)	MTBCM (Hours)	MTTCM (Hours)
AIR INTAKE SYSTEM (GT-AIS)	0.01	975612.0	975612.0	1.0	1.0000	1.29	6795.5	6795.5	1.0
DUMPERS (GT-AIS04)	0.01	975612.0	975612.0	1.0	1.0000	1.29	6795.5	6795.5	1.0
BALANCE OF PLANT (GT-BOP)	0.00	0.0	0.0	0.0	0.9989	0.00	0.0	0.0	0.0
TESTING (GT-BOP04)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
CLEANING (GT-BOP05)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
INSPECTION (GT-BOP06)	0.00	0.0	0.0	0.0	0.9989	0.00	0.0	0.0	0.0
COMBUSTION SYSTEM (GT-CMB)	0.00	1951224.0	1951224.0	4.0	1.0000	0.64	13591.0	13591.0	4.0
FUEL NOZZLES (GT-CMB02)	0.00	1951224.0	1951224.0	4.0	1.0000	0.64	13591.0	13591.0	4.0
CONTROL & INSTRUMENTATION (GT-CTI)	0.04	216802.7	150094.2	8.3	0.9999	5.80	1510.1	1045.5	8.3
CONTROL & INSTRUMENTATION (GT-CTI)	0.00	1951224.0	1951224.0	1.0	1.0000	0.64	13591.0	13591.0	1.0
CIRCUIT BREAKERS (GT-CTI01)	0.00	0.0	1951224.0	0.5	1.0000	0.00	0.0	13591.0	0.5
ELECTRICAL MODULE (GT-CTI02)	0.02	487806.0	325204.0	7.2	1.0000	2.58	3397.8	2265.2	7.2
GAUGES (GT-CTI03)	0.00	1951224.0	975612.0	1.0	1.0000	0.64	13591.0	6795.5	1.0
SWITCHES (GT-CTI04)	0.01	975612.0	975612.0	29.0	1.0000	1.29	6795.5	6795.5	29.0
WIRING (GT-CTI05)	0.00	1951224.0	1951224.0	4.0	1.0000	0.64	13591.0	13591.0	4.0
EXHAUST SYSTEM (GT-EXH)	0.00	1951224.0	975612.0	5.5	1.0000	0.64	13591.0	6795.5	5.5
EXHAUST DUCTING (GT-EXH01)	0.00	0.0	1951224.0	1.0	1.0000	0.00	0.0	13591.0	1.0
EXHAUST FAN (GT-EXH03)	0.00	1951224.0	1951224.0	10.0	1.0000	0.64	13591.0	13591.0	10.0
FUEL SYSTEM (GT-FLS)	0.04	243903.0	130081.6	5.0	1.0000	5.16	1698.9	906.1	5.0
BOOST PUMP (GT-FLS02)	0.01	650408.0	650408.0	2.0	1.0000	1.93	4530.3	4530.3	2.0
FILTERS (GT-FLS04)	0.00	1951224.0	278746.3	1.1	1.0000	0.64	13591.0	1941.6	1.1
GOVERNOR (GT-FLS07)	0.00	1951224.0	1951224.0	2.0	1.0000	0.64	13591.0	13591.0	2.0
MAIN FUEL PUMP (GT-FLS08)	0.00	1951224.0	1951224.0	4.0	1.0000	0.64	13591.0	13591.0	4.0
STRAINER (GT-FLS13)	0.00	0.0	0.0	0.0	1.0000	0.00	0.0	0.0	0.0
VALVES (GT-FLS14)	0.01	975612.0	975612.0	27.5	1.0000	1.29	6795.5	6795.5	27.5
PIPING (GT-FLS15)	0.00	0.0	1951224.0	1.0	1.0000	0.00	0.0	13591.0	1.0
GENERATOR (GT-GNR)	0.04	216802.7	216802.7	33.3	0.9998	5.80	1510.1	1510.1	33.3
GENERATOR (GT-GNR)	0.00	1951224.0	1951224.0	72.0	1.0000	0.64	13591.0	13591.0	72.0
TURBINE COUPLING (GT-GNR10)	0.03	278746.3	278746.3	32.2	0.9999	4.51	1941.6	1941.6	32.2
VOLTAGE REGULATOR (GT-GNR11)	0.00	1951224.0	1951224.0	2.0	1.0000	0.64	13591.0	13591.0	2.0
LUBE OIL/HYDRAULIC SYSTEM (GT-LBO)	0.02	390244.8	177384.0	1.6	1.0000	3.22	2718.2	1235.5	1.6
LUBE OIL FILTER (GT-LBO03)	0.00	0.0	650408.0	2.0	1.0000	0.00	0.0	4530.3	2.0
VALVES (GT-LBO11)	0.00	0.0	1951224.0	1.0	1.0000	0.00	0.0	13591.0	1.0
PIPING (GT-LBO12)	0.02	487806.0	487806.0	1.8	1.0000	2.58	3397.8	3397.8	1.8
SEALS (GT-LBO13)	0.00	1951224.0	650408.0	1.3	1.0000	0.64	13591.0	4530.3	1.3
REDUCTION GEARBOX (GT-RGB)	0.00	1951224.0	1951224.0	360.0	0.9998	0.64	13591.0	13591.0	360.0
REDUCTION GEARBOX (GT-RGB)	0.00	1951224.0	1951224.0	360.0	0.9998	0.64	13591.0	13591.0	360.0
STARTING SYSTEM (GT-STS)	0.13	67283.6	45377.3	28.6	0.9994	18.69	468.7	316.1	28.6
STARTING SYSTEM (GT-STS)	0.00	1951224.0	1951224.0	2.0	1.0000	0.64	13591.0	13591.0	2.0
BATTERY (GT-STS06)	0.08	108401.3	60975.8	3.3	1.0000	11.60	755.1	424.7	3.3
STARTING SHAFT (GT-STS07)	0.02	390244.8	390244.8	93.5	0.9998	3.22	2718.2	2718.2	93.5
STARTER MOTOR (GT-STS08)	0.02	390244.8	390244.8	130.8	0.9997	3.22	2718.2	2718.2	130.8
TURBINE (GT-TRB)	0.02	390244.8	390244.8	1158.4	0.9970	3.22	2718.2	2718.2	1158.4
TURBINE (GT-TRB)	0.02	487806.0	487806.0	1398.0	0.9971	2.58	3397.8	3397.8	1398.0
BEARING (GT-TRB05)	0.00	1951224.0	1951224.0	200.0	0.9999	0.64	13591.0	13591.0	200.0

Discussion

R. H. Gauger (Holmes & Narver): This is an excellent survey and is the most comprehensive one available for the 600–1800-kW size range of diesel and gas-turbine-generating units. The results are not what I would have expected, and users of these data should be altered to differing results from surveys made by others. I have made a number of surveys of the reliability of diesel and gas-turbine-generating units of various sizes and will be making a comparison of the results with this new survey.

L. D. Monaghan (Hartford Steam Boiler Inspection and Insurance Company): My comments are directed at the corrective maintenance category. The corrective maintenance code should indicate why the corrective maintenance was necessary. The cause should address such things as lack of preventive maintenance or a manufacturer's defect. Knowing the reason for the maintenance would help the user of these data to differentiate between a manufacturing problem and an operational problem. Another suggestion is for the maintenance category to be subdivided into routine, preventive, and lack of maintenance.

Richard H. McFadden, Peter L. Appignani, and Gary DeMoss (Science Applications International Corporation): This paper represents a significant new base of reliability data for the most popular types of small generating units and will be a valuable resource for intelligent decisions between diesel- and gas-turbine-powered generation. The authors' component coding approach is excellent and would be a good basis for a standardized "component taxonomy" for diesel and gas-turbine generators.

The paper raises some questions for which answers would be valuable to system and reliability engineers contemplating similar projects, and we would appreciate the authors' comments on them.

First, as the authors remark, failure to start is the predominant failure mode of units of both types in "standby" service. (Independently developed reliability statistics on both nuclear-plant standby diesels and utility peaking gas turbines tend to confirm this observation.) As the authors also imply, the distinction between standby and continuous service is blurred in the industrial-commercial environment, because even the sets in nominally "continuous" duty typically operate cyclically, with many more starts than a base-loaded generating unit. Since starting reliability seems to be a critical RAM parameter, why are failure rates calculated exclusively in terms of failures per unit-year rather than failures per demand? The level of detail of the failure analysis in the paper suggests that the raw data were sufficient to distinguish between time- and demand-related failures and allow both failure rate per-unit time and failure-probability per demand to be calculated.

Second, although the RAM data were not conclusive and judgments about the relative merits of diesels versus gas turbines probably were outside the scope of this study, did the authors develop any insights into the optimum selection for various industrial, commercial building, and institutional applications?

P. F. Albrecht (General Electric Company): A key parameter for standby units is starting reliability. The text mentions starting reliability but does not give any statistics. I cannot determine how starting failures were treated. I assume they were counted as forced outages.

Another important event is "failed while not running." This is not discussed at all. These could be failures discovered by periodic testing or inspection. Thus, test frequency may be a very important parameter in determining operating availability. It does not appear that this factor was considered in the survey.

Basically, the authors have analyzed the data using a conventional two-state model approach. They have expressed results on both a period-hour and operating-hour base to suit a "variety of applications." In fact, a two-state model is not very useful for standby units, and the results presented are therefore difficult to use.

Pat O'Donnell (El Paso Natural Gas Company): The reliability survey data on diesel and gas-turbine generators collected by ARINC Research Corporation appear to provide an excellent data base for meaningful reliability studies on important equipment types. The results reflect an obvious intense and praiseworthy effort in assembling a well-organized and complete data base for its intended purpose. Personal plant visits, as reported in the paper, especially add to the credibility of the results. Although particular details on applications and circumstances of use are not listed, the number of plants, the number of power systems, periods of time, and the number of events counted are impressive and reflect very credible results.

As with any reliability survey, a given set of results always leads to questions and concerns related to any user's given experience background, and usually further manipulation and analysis of the data are required. My intent is to point out some questions and concerns that, hopefully, will lead to additional analyses. In many industries, economic studies comparing gas turbine/generators with reciprocating engine/generators are usually straightforward and simple, with the exception of reliability comparisons and the effects of reliability on economics. Hopefully, these new data will add a missing link and allow more meaningful and accurate comparisons to be made.

An important concern in evaluating the categories surveyed is the speed of the diesel engine. Typically, continuous duty units are designed and applied to run at slower speeds than standby units. "High-speed" reciprocating engines (e.g., 1200 r/min and higher) require frequent maintenance and predictable repair downtime compared with slow-speed units that simply do not experience the same mechanical stress. One would expect a higher failure rate or higher frequency or maintenance, or both, for high-speed engines than for slower speed engines. Will the data allow speed ranges to be identified and corresponding reliability comparisons to be made?

Starting reliability is an important concern, especially for standby or emergency applications. It is unclear if the failures shown for "starting systems" also mean "failures to start." The data might, in some cases, reflect component failures even though the generator set successfully started. Actual "failures to start" would be beneficial in comparing diesel engines with gas turbines, since there are many who believe there is a significant difference. Whether a unit is locally or remotely started normally requires an assessment of reliability in starting. The impact of a failure to start is obviously different when personnel are on site to address a problem immediately as compared with when personnel must travel to a site to address a problem.

Another concern that is important to reliability is the type of starter used. It appears from the data presented here that air and electric motors are two types of starters used. In the natural gas industry, expansion gas turbines are commonly used for starting turbines and definitely are much more reliable than electric starters, primarily because of the available gas supply. Can a closer analysis be made comparing the air systems with the electric motors?

Also regarding starting, the results reflect significant difference in failure rates between "continuous" and "standby" diesel units and "continuous" and "standby" gas turbines and state that this may be related to differences in actual in-use hours. One would also expect that the frequency of starting is different and might impact failure rates. Can this analysis be made?

The fuel system appears to be a significant contributor to failures. It is interesting that on "continuous" gas turbines, the fuel system is the least reliable part of the package. It would be beneficial if reasons could be identified. Are different types of fuels involved? If so, will the data collected allow comparing failure rates for each type?

The tabulated results in Appendix II, Tables VIII and IX, of the report suggest that possibly not all diesel units are truly packaged type (e.g., cooling towers, water heater). Can the data be refined further to identify which units are truly self-contained?

A last point of concern regards maintenance. A reciprocating engine is expected to be more demanding in routine maintenance requirements than a gas turbine. To qualify this statement, this is to say that it is easier to leave a gas turbine unattended, once it is running, than it is a reciprocating engine, especially if they are running continuously. There are various reasons why, some of which are the way the units are typically instrumented for protection and the number of moving parts and wear. If the MTBCM data include scheduled maintenance cycles, a comparison of failure rates for different cycles would be meaningful.

The results here reflect an excellent collection of data and should be very beneficial in making comparisons of these equipment types. In the application of reliability data an inevitable concern is the reason for differences in reliability between equipment types and applications. One obvious practical benefit is to be able to identify what corrective actions are encouraged by

TABLE XII
COMPARISON OF DIESEL AND GAS-TURBINE STARTING RELIABILITY STUDIES

Source	Number of Units	Start Attempts	Failed Starts	Starting Reliability
		Gas-Turbine Starting Reliability Studies		
ARINC Research Corporation[1]	7	3,555	17	0.9952
Booz, Allen & Hamilton[2]	34	12,316	80	0.9935
Kongsberg Dresser Power[3]	38	17,749	141	0.9921
AT&T[4]	28	13,644	106	0.9922
		Diesel Starting Reliability Studies		
ARINC Research Corporation[1]	—	—	—	0.97
Electric Power Research Institute (EPRI)[5]	155	22,320	83	0.9963
Consumers Power Company—Big Rock Point[6]	2	669	12	0.9821
Northeast Utilities—Millstone[6]	3	652	3	0.9954
Northeast Utilities—Connecticut Yankee[6]	2	642	2	0.9969
Commonwealth Edison Company—Zion[6]	4	1,693	30	0.9823
Consolidated Edison Company of New York, Inc.—Indian Point[6]	6	424	4	0.9906
Institute of Nuclear Power Operations (INPO)[7]	←	Data not available	→	0.9120
EPRI[8]	←	Data not available	→	0.9829

[1]ARINC Research Corporation. *Final Report—RAM Study of Diesel and Gas-Turbine Generator Sets*. Publication 4219-03-01-4803, October 1988.

[2]Booz, Allen Applied Research. *Small Gas Turbine Start Investigation*. April 1970.

[3]Kongsberg Dresser Power. Internal Study Comparing Diesels with Gas-Turbine Engines (unpublished), 1984.

[4]AT&T. Internal Study for Gas-Turbine Reliability (unpublished), 1980.

[5]Electric Power Research Institute. *Reliability of Emergency Diesel Generators at U.S. Nuclear Power Plants*. NSAC 108, September 1986.

[6]U.S. Nuclear Regulatory Commission. *Nuclear Computerized Library for Assessing Reactor Reliability (NUCLARR)*. NUREG/CR-4639 EGG-2458, Volume 5, RX, June 1988.

[7]Institute of Nuclear Power Operations. *Nuclear Plant Reliability Data System, 1982 Annual Report*, 1983.

[8]Electric Power Research Institute. *Diesel Power Reliability at Nuclear Power Plants: Data Preliminary Analysis*. NP-2433, June 1982.

a user and which are encouraged by a manufacturer. Hopefully, additional analyses will be made addressing the concerns of this discussion and other similar concerns stimulated by the results presented here.

Closure

The authors appreciate the thorough review and the many constructive comments and recommendations offered in the preceding discussion. While space limitations prohibit addressing all of the suggestions offered, a response to some of the more frequently cited comments is provided in the following paragraphs.

Obtaining data on unit starting reliability was one of the objectives of the study. However, most of the plants surveyed did not record data necessary to determine starting reliability. While it was often possible to identify start failures through interpretation of the maintenance event descriptions, the number of start attempts was typically not retrievable. In addition, our discussions with plant personnel indicated that many start failures were corrected through minor adjustments that were usually not documented in maintenance or operating records. Because of the limited data available, starting reliability statistics were not presented in the paper.

Some information on starting reliability was obtained during the study. These data are presented in Table XII. Seven gas-turbine units provided data on start attempts and start failures during periodic testing. To obtain estimates of diesel starting reliability, we surveyed plant managers of four of the standby diesel plants to estimate the number of start failures in 100 attempts. We then averaged these estimates to obtain an estimated diesel starting reliability. Table XII also shows a comparison of values for diesel and gas-turbine starting reliability.

With regard to maintenance, data were categorized on the basis of the nature of the individual maintenance task performed for each event. The maintenance codes do not refer to the cause of failure or the overall maintenance program for the plant. Additional reduction and analysis of the collected data would be required to investigate these issues.

An important feature of the computerized data base developed in this survey is the ability to sort and arrange the data to analyze specific issues regarding plant configuration, design, or operation. The preceding discussions have provided several beneficial suggestions for additional analyses. The results of additional data analyses or data collection activities under this program will be discussed in subsequent papers.

References

[1] *Government-Industry Data Exchange Program Remote Terminal Users Guide*, GIDEP Operations Center, Oct. 1987.

[2] *Power Reliability Enhancement Program (PREP) GO Reliability/Availability Data Bank Development Effort*, Illinois Inst. Technol. Res. Inst. Reliability Analysis Center, Aug. 1984.

[3] *IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems*, ANSI/IEEE Standard 493, 1980.

[4] *IEEE Trial-Use Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity*, ANSI/IEEE Standard 762, 1980.

[5] *Nuclear Power Reliability Data System (NPRDS) Data Retrieval Manual*, Inst. Nuclear Power Operations, INPO 83-034, Rev. 4, Sept. 1986.

[6] *Major Fixed Command, Control, and Communications Facilities Power Systems Design Features Manual*, U.S. Army Corps of Engineers, Huntsville Division, HNDSP-82-043-SD, Ch. 9, Aug. 1986.

[7] *RAM Study of Diesel and Gas Turbine Generator Sets*, ARINC Res. Pub. 4219-03-01-4803, Oct. 1988.

Clayton A. Smith received the B.S. degree in aerospace engineering from the University of Maryland, College Park.

He is a Staff Engineer for ARINC Research Corporation. He is responsible for the development of data bases for many reliability, availability, and maintainability projects, including those for the Electric Power Research Institute (EPRI), the Gas Research Institute (GRI), petroleum refineries, electric utilities, and the Army Corps of Engineers. He also conducts analyses to investigate component criticality, cost optimization, and modification evaluations.

Michael D. Donovan (A'86) received the B.S. degree in mechanical engineering from Vanderbilt University, Nashville, TN, and the M.S. degree in industrial management from the Georgia Institute of Technology, Atlanta.

He is the Manager of the Industrial Process Group of ARINC Research Corporation and is responsible for the company's engineering services to clients in energy, petrochemical, and manufacturing industries.

Mr. Donovan is Chairman of Station Operations for the Energy Development and Power Generation Committee of the Power Engineering Society and is a Registered Professional Industrial Engineer in the State of Georgia.

Michael J. Bartos received the B.S. degree in mechanical engineering from Pennsylvania State University, University Park, in 1985.

He is currently a Mechanical Engineer in the Power Reliability Enhancement Program (PREP) with the U.S. Army Corps of Engineers, Engineering and Housing Support Center (EHSC). He has been with the PREP program since 1987. His experience with the program includes engineering support for operating power plants and efforts to enhance reliability, survivability, and operation/maintenance of critical command, control, communications, and intelligence facilities and utilities. He was with the U.S. Navy's Cruise Missile Branch of the Airborne Weapons Engineering Division where he served as a Project Engineer from 1985. His experience in the area was design verification, lot acceptance tests, and maintenance concerns. He is also involved in tutorial disadvantaged youth in the Washington, DC, area.

Reliability/Availability Guarantees of Gas Turbines and Combined Cycle Generating Units

By
Thomas E. Ekstrom

IEEE Transactions on Industry Applications
Vol. 31, No. 4, July/August 1995, p. 691–707

Reliability/Availability Guarantees of Gas Turbine and Combined Cycle Generating Units

Thomas E. Ekstrom

***Abstract*— This paper is an updated and revised version of the 1992 ASME paper 92-GT-208 "Reliability measurements for gas turbine warranty situations." It recognizes that reliability performance is receiving significant and increasing attention in the bid requests for new gas turbine generating units. Reliability guarantees backed by liquidated damages clauses are becoming more the rule rather than the exception. But the power generation industry does not have a universally accepted set of reliability measurements, and the more commonly used measurements are not always used appropriately, nor are they sufficiently refined for the warranty situation.**

This paper is intended to provide the guidance, structure, and refinement needed for meaningful reliability measurements and reliability warranties.

Four key areas of reliability measurement: starting reliability, running reliability, availability and equivalent availability are separately explored. Within each of these areas there is the flexibility and the need to adapt the measurement system to the varied operating regimes and philosophies encountered such as: peaking versus continuous service, limited scopes of supply, different levels of maintenance intensity, chargeable versus nonchargeable outage events and emotional/political/optical acceptability (i.e., 3% Forced Outage Factor versus 40% Forced Outage Rate). Warranty structuring rationale and suggested contract language are provided to address such needs as a rigorous and explicit operating log, certification of data, measurement uncertainty, assurance of readiness, and risk assessment.

The suggestions presented herein have been constructed with logic and fairness. They have been applied with good acceptance to over 30 contracts in the past three years. This paper will be beneficial to all architect engineers, utilities, independent power producers, and OEM's that become involved with the measurement of reliability or the structuring of reliability warranties.

I. Introduction

IT HAS been said that gas turbine value is measured in terms of performance and reliability. And to insure the receipt of that value, the electric utility industry is increasingly seeking warranties on both performance and reliability in its contracts for new gas turbine power plants. But common practices and the available standards for measuring reliability are inadequately structured for warranty situations. This paper addresses these needs. In this paper the word "reliability" is frequently used in the broad sense. Reliability warranties may typically apply to any of the following specific measurements:

Paper ICPSD 94–52, approved by the Power Systems Engineering Committee of the IEEE Industry Applications Society for presentation in part at the 1992 American Society of Mechanical Engineers Meeting, and in full at the 1994 IEEE Industry Applications Society Annual Meeting, Denver, CO, October 2–7. Manuscript released for publication February 13, 1995.

The author is with GE Power Generation Engineering, Gas Turbine Applications Engineering, Schenectady, NY, 12345-6001 USA.

IEEE Log Number 9411435.

1) Starting Reliability: The expected likelihood that a generating unit can successfully start on demand and/or within a given time period.

2) Running Reliability: The expected likelihood that a generating unit can provide electricity when requested. Measurements of running reliability deal with unplanned events and generally exclude all outages associated with scheduled maintenance activities.

3) Availability: The expected portion of period time (typically a year) that a generating unit is capable of providing electricity. Availability considers all outage activity, both planned and unplanned, forced and scheduled.

4) Equivalent Availability: Similar to availability but further refined by capacity adjustments to reflect the cumulative energy production capability. It becomes the expected portion of *energy output* available over a period of time (typically one year) and is applied where the availability measurement must also reflect the effect of reduced capacity operating modes. The concept of "Equivalent . . . " can also be applied to running reliability measurements.

II. Current Standards and Data Collection Systems

Technically speaking, the domestic (USA) electric utility industry has one formal standard for reliability terminology. It is ANSI/IEEE Standard 762-1987, entitled "IEEE Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity" [1]. It was written for base-loaded power plants and defines no less than 66 reliability-related terms plus some 25 performance indexes (none of which are explicitly named "reliability" or "running reliability.") IEEE Std 762 is fairly new and to the author's current knowledge, there are no industry databases or operator data collection systems that are strictly based on the IEEE Std 762 definitions. The more commonly used definitions in the United States are those of the North American Electric Reliability Council (NERC), as applicable to its Generating Availability Data System (GADS). A significant number of domestic (USA) utilities supply annual operating data to the GADS data base. The NERC GADS definitions are slightly different from the IEEE Std 762 definitions but NERC is gradually changing its definitions to be more in line with the IEEE standard. And despite the IEEE and NERC definitions, the majority of utilities still use their own "home-grown" traditional measures which tend to combine classical reliability theory with specific system configuration, operating or administrative needs.

The objectives of IEEE and NERC relate to the gathering and presenting of *broad system operational data* on a consistent basis. But component failure rate data and failure cause data have not been rigorously kept and no effort has been made to assess maintenance intensity effect. *Force majeure* events are not subtracted. Downtime is not segregated into active repair effort, waiting time, or unapplied time. Consequently, the IEEE and NERC definitions structures have not been adequate to support the needs of equipment reliability engineers nor to support real-world reliability/availability warranties. Nonetheless, the concepts, definitions, and formulas of IEEE Std 762 and NERC GADS still provide an excellent starting point. The terms and recommendations in this paper utilize, expand upon, and generally flow with these "standards."

Another database receiving increasing attention is the Operational Reliability Analysis Program (ORAP) which was devised by GE in 1976 and is currently managed by Strategic Power Systems Inc., a private company in Albany, NY. It utilizes the old standard terminology of Edison Electric Institute but was set up as an "events-based" database to specifically serve reliability engineering needs. It presently includes more than 4500 unit-years of comprehensive gas turbine operating data and provides fleet performance reports and failure rate data to the users, EPRI, architect engineers and the OEM's. Today, with the ever-increasing flexibility of computers, systems such as the ORAP system have the capability to support the most detailed categorization of events and then provide for multiple analysis and reporting. From one set of operating data, the computer can generate the standard fleet performance reports, the appropriately categorized NERC GADS data (or results), the utility's preferred internal performance report and a unit or plant warranty performance level measurement set under custom-tailored warranty conditions.

III. Starting Reliability

Starting Reliability (SR) is easily understood as the ratio of the number of successful starts to the number of attempted starts.

$$\text{Starting Reliability} = \frac{\text{successful starts}}{\text{attempted starts}} \quad \text{(NERC)}. \tag{1}$$

However, when starting reliability is to be measured carefully, there are a number of "special situations" that must be considered, adjusted for, and sometimes contractually qualified. The most typical are:

- multiple initiations of the "start" command without intervening corrective action(s),
- "test" starts and "maintenance" starts,
- starting failures caused by other than contract-furnished equipment,
- starting time allowance period,
- operator or procedural errors,
- start sequence aborts by operator or dispatcher discretion with no equipment failure,
- load level reached for a "successful start," and
- starting reliability measurements for components, subsystems and partial plants.

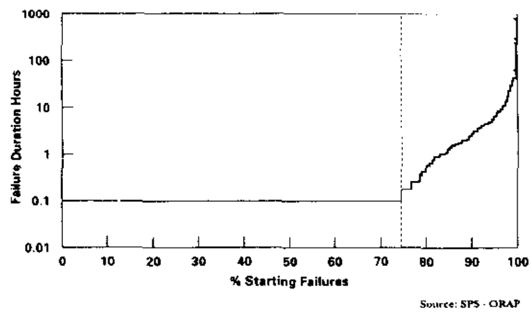


Fig. 1. Starting failure outage times. Cumulative distribution—MS7001E/EA units 1978–1989.

To illustrate the importance of the above "special considerations," consider the concept of the starting time allowance period as incorporated in the IEEE standard but not in the NERC GADS or standard ORAP definitions. The IEEE standard allows that repeated initiations of the starting sequence, within a user-specified period (typically 20 or 30 min) be counted as a single attempt. The significance of this distinction is evident by the fact that 74% of the starting failures (see Fig. 1) reported in the ORAP data base under the NERC definition are followed by a successful start within six minutes time of the "failure" and have minimal impact to the service demand request. When a five-year ORAP history of GE MS7001E/EA units was assessed the starting reliability averaged 93% by the NERC definition but 98.2% by the IEEE Std 762 definition!

The IEEE Std 762 formula for starting reliability basically enables fair treatment of all the "special situations" described previously by focusing only on the number of chargeable failures to start. This is accomplished by making a subtle formula change to

$$\text{Starting Reliability} = \frac{\text{SS}}{\text{SS} + \text{SF}} \quad \text{(IEEE)} \tag{2}$$

where SS = [Chargeable] Starting Successes, and SF = [Chargeable] Starting Failures.

IEEE Std 762 then offers some basic qualifications through its definitions. But warranty situations require expanded qualification as suggested here along the lines of IEEE Std 762.

A *Qualifying Starting Attempt* is the action intended to bring a unit from shutdown to the in-service state under conditions that qualify for inclusion in the warranty. Repeated initiations of the starting sequence within the allowable specified starting time period or without accomplishing corrective repairs are counted as a single attempt.

A *Chargeable Starting Success* is the occurrence of bringing a unit through a qualifying starting attempt to the in-service state within a specified period, as evidenced by maintained closure of the generator breaker to the system.

A *Chargeable Starting Failure* is the inability to bring a unit through a qualifying starting attempt to the in-service state within a specified period for failure reasons chargeable to the warranty. Repeated failures within the specified starting period are to be counted as a single starting failure.

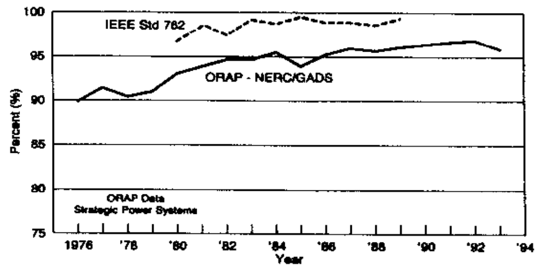


Fig. 2. Starting reliability MS7001 domestic units.

A third formula for starting reliability is used in the ORAP system for engineering analysis of component and subsystem performance.

$$\text{Starting Reliability} = \frac{SA - SF}{SA} \quad \text{(Engineer's)} \qquad (3)$$

where SA = Qualifying Starting Attempt, and SF = [Chargeable] Starting Failures.

This "Engineer's" formula, like the IEEE formula, accommodates the "special situations" fairly well and actually offers the most representative measure of equipment performance. But it tends to err on the optimistic side while the NERC-GADS and IEEE formulas tend to err on the pessimistic side. For example, a starting attempt aborted midway through the start sequence by the operator, but not associated with any equipment failure, would be counted as a failed start by NERC-GADS, would not be counted at all under IEEE Std 762, and would be counted as a successful start by this ORAP formula.

When selecting a measurement formula and warranty context for starting reliability guarantees, there need to be rules: What is chargeable, and what is not? The maintenance-readiness environment should be addressed. And the measurement should statistically reflect the inherent starting reliability of the equipment. Financial penalties should not be incurred in a warranty situation simply due to the *natural randomness* of starting failures. Here are some examples of SR warranty considerations:

1) Repair verification starts and failures-to-start from equipment not furnished under the contract should not be chargeable to the warranty.
2) If the equipment has not been successfully started within a reasonable period (e.g., 30 days) then, for compromise of readiness, the next starting attempt should not be considered a qualifying start attempt.
3) In order to realize the significantly higher SR levels associated with the IEEE starting time allowance clause, there should be technically competent supervision and appropriate maintenance personnel available at site to expeditiously facilitate correction of the minor and "procedural" errors that typically account for the five-minute start-up delays. Remotely dispatched sites typically do not have this benefit. Fig. 2 illustrates the numeric magnitude of this difference.

A good measure of starting reliability considers measurement precision and representativeness, commonly referred to as measurement uncertainty. It takes 100 start attempts for the data alone to be precise to the nearest one percent. And it takes 1000 start attempts for the measurement to statistically represent the true-inherent equipment SR with one-percent accuracy at the 90% confidence level! Therefore it is always recommended to combine the starts data from all similar units at the same site and maybe for multiple years to obtain a better and more representative data set. Obviously a machine that is started less than 50 times per year is a poor candidate for a single unit starting reliability warranty. Here is a way, however, that this measurement uncertainty can be fairly addressed.

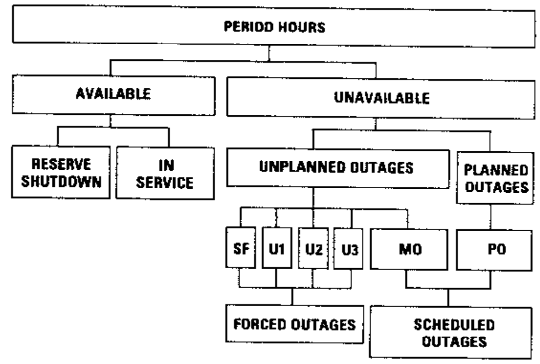


Fig. 3. Conceptual classification of outage time (NERC GADS).

If the starting reliability measurement must be made with an accumulation of less than 500 start attempts, the statistical measurement uncertainty shall be recognized by providing an allowance from the guarantee level. The Measurement Uncertainty Allowance shall adjust the point of damages initiation based on the cumulative binomial probability function and the actual number of start attempts so as to assure with 75% confidence that the indicated (measured) shortfall is due to equipment deficiency rather than the random nature of failure occurrences.

The author recommends that the IEEE Std 762 formula be used for starting reliability guarantees since it is most universally acceptable, allows focus on only the chargeable starting failure events, and is already set up as a published national standard. Starting reliability guarantees are not recommended for base load and continuous service units that experience infrequent starting. Appendix A provides a suggested generic write-up for a multi-unit Starting Reliability warranty.

IV. Outage Classifications

Before discussing running reliability and availability, which are primarily time-based measurements, one should review the principal classifications of outage time. For this, a picture is worth a multitude of words and this "picture" (see Fig. 3) is based on the familiar NERC GADS definitions.

1) SF = *Starting Failure*. Under IEEE Std 762, this is called a Class 0 Unplanned Outage.
2) U1 = *Immediate Unplanned Outage*. IEEE Std 762 call this a Class 1 Unplanned Outage and both NERC and IEEE allow assignment to this classification from

either the in-service (running) state or from the shutdown (nonrunning) state. IEEE additionally permits scheduled outage extension time to be reclassified as Class 1 depending on the cause of the extension. The ORAP reporting system takes a different approach to U1, U2, and U3 forced outages which will be discussed later. U1 failures are obviously the most critical failure events.

3) U2 = *Delayed Unplanned Outage*. Similar to U1 but less urgent; NERC-GADS generally allows the machine to delay the outage to the end of its daily run. IEEE Std 762 calls this a Class 2 Unplanned Outage and more specifically requires that unit be removed from the in-service state within six hours.

4) U3 = *Postponed Unplanned Outage*. Both NERC GADS and IEEE identify this as an outage that can be postponed beyond the U2 level of urgency but must be removed from the in-service state before the end of the next weekend. IEEE Std 762 identifies U3 outages as Class 3 Unplanned Outages.

5) MO = *Maintenance Outages*. IEEE Std 762 identifies maintenance outages as Class 4 Unplanned Outages and with NERC GADS qualifies these outages as those that can be delayed beyond the next weekend but must be attended to before the next [long-lead] planned outage. The ORAP definition of maintenance outage is slightly broader as it picks up a few of the U2 outages and many of the U3 outages. Note that maintenance outages occur for unplanned reasons but can be sufficiently delayed to be classed as "scheduled" outages.

6) PO = *Planned Outages*. Both IEEE Std 762 and NERC GADS identify planned outages as those that are scheduled well in advance and have a predetermined duration. Extensions of planned outage are noted as such under NERC GADS and continue to be counted as more planned (and scheduled) outage hours. But according to IEEE, planned outage extensions may be retained as unplanned outage extensions or reassigned to Class 1 or Class 0 unplanned outages depending upon extension cause.

Administrative Outage Hours (AOH) are a category not identified under either IEEE Std 762 or NERC GADS but very necessary for warranty situations. It provides a charging category (or location) for outage hours that might not be chargeable under the warranty such as *force majeure* events, waiting time, nonapplied time, noncovered equipment outages, etc. Furthermore, it can also be used to separate the service intensity/effectiveness aspects from the nominal inherent equipment aspects in cases where the warrantor is not responsible for providing the maintenance service. In application, the AOH hours are removed from the IEEE or NERC unplanned outage hours and then either removed totally from the measurement or credited as available hours.

As mentioned previously, the basic ORAP reporting system treats the forced outage categories differently from the NERC GADS and IEEE classifications. The distinction primarily relates to whether the unit was running or in the shutdown state at the time of initiation of the outage state. The four standard ORAP forced outage categories are:

1) FS–*Starting Failure*
2) FOA–*Automatic Trip* from the running state
3) FOM–*Manual Trip* from the running state
4) FU–*Forced Unavailability* from the shutdown state.

The ORAP maintenance outage categories roughly correspond to the NERC GADS' MO and PO and are:

1) MU–*Maintenance Unscheduled*
2) MS–*Maintenance Scheduled.*

The ORAP outage classifications plus identification of noncurtailing events particularly serve the reliability engineering needs and enable the measurement of failure rate from the running state. MTBF data for gas turbines are generally more appropriate when based on service time and failures from the running state. The ORAP system also reports concurrent maintenance activities to assist design engineers and to better support MTTR assessments. NERC GADS is planning to pick up these capabilities.

As can be seen from above, the NERC GADS, SPS-ORAP, and IEEE outage classification systems are somewhat similar, *but not identical*. The variations in outage classification definitions plus operator judgement on classifications are quite minor in the aggregate of many unit-years of data. But in the context of measuring performance for a single unit for a single year, and then considering financial penalty or "liquidated damages," such variations can be extremely important. A well-written warranty contract document will greatly reduce future conflict over rules and operator interpretations.

V. Running Reliability

Reliability is defined (in essence) as "the probability that the equipment, or system, can fulfill its function *for the planned period of need*." But while there is widespread general agreement with this concept, there is unfortunately a large number of significantly different measurement formulas being applied to quantify "reliability." This group is often referred to as "Running Reliability" (RR) measurements (to distinguish them from starting reliability measurements) and their one point of commonality is that they all generally exclude planned shutdowns from the measurement.

For the sake of reliability understanding, and to more quickly relate to the *many* formulas faced by users, A/Es and OEM's; some of the more commonly used formulas will be defined, explained and compared for different operating service profiles. Please note that some formulas are better suited to specific warranty or engineering situations than are other formulas.

A. $\mathrm{RR} = (1 - \mathrm{FOF})$ [GT traditional formula] (4)

where FOF is the Forced Outage Factor and

$$\mathrm{FOF} = \frac{\text{Forced Outage Hours}}{\text{Period Hours}}. \tag{5}$$

The author's company has traditionally used this formula for reliability because: 1) the Forced Outage Factor tends to be somewhat independent of service duty, and 2) the FOF can

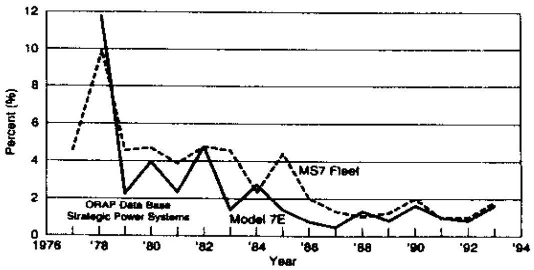


Fig. 4. Forced outage factor. MS7001 domestic (USA) units.

be directly subdivided to the contributing elements. Forced Outage Factor is formally defined by both NERC GADS and IEEE Std 762; it typically runs in the 1% to 4% range (see Fig. 4) and is a reasonably well accepted reliability measure for high use machines. It is the reliability measure used in ORAP. The minor problem with this measure is that while an FOF of 2% yields a good reliability number of 98%, most users/operators are not impressed with the thought of 175 forced outage hours per year on machines used only 100 to 500 service hours per year. The more common and preferred form of this traditional GT formula, is as follows:

$$\mathrm{RR} = \frac{\text{Period Hours} - \text{FOH}}{\text{Period Hours}}. \tag{6}$$

For warranty situations, FOH are *chargeable* forced outage hours.

B. RR = (1 − UOF) ["UOF" formula] (7)
where UOF is the Unplanned Outage Factor and

$$\mathrm{UOF} = \frac{\mathrm{FOH} + \mathrm{MOH}}{\mathrm{PH}} \tag{8}$$

FOH	Forced Outage Hours,
MOH	unplanned Maintenance Outage Hours, and
PH	Period Hours.

This UOF formula is similar to the traditional GT formula (4) except that it includes all unplanned outages (forced plus maintenance). Some ORAP historical data has shown that the Maintenance Outage Factor runs at about two-thirds of the Forced Outage Factor. So the "example" machine with a 2% FOF might have 1.3% MOF for a total of 3.33% Unplanned Outage Factor and a "UOF Reliability" of 96.7%.

C. RR = (1 − FOR) [utility FOR formula] (9)
where FOR is the Forced Outage Rate and

$$\mathrm{FOR} = \frac{\text{Forced Outage Hours}}{\text{Forced Outage Hours} + \text{Service Hours}}. \tag{10}$$

The Forced Outage Rate (FOR) is a long established utility industry measurement formally defined by both NERC GADS and IEEE. It works fairly well on high use machines and it is often used for utility reliability calculations including loss of load probability planning. It loses its appropriateness and attractiveness when applied to low usage machines in standby or traditional "peaking" service. The "example" machine with 175 forced outage hours and 100 service hours per year has an FOR of 63.6% and a reliability of 36.4%! The optics are bad. Part of the problem with FOR, as a measurement, is that no credit is given for reserve shutdown time when the unit is fully available on standby. Another part of the problem is that *all elapsed time* forced outage hours (FOH) are debited even though a large percentage of the FOH might occur during periods of nondemand.

D.

$$\mathrm{RR} = \frac{\mathrm{PH} - \mathrm{FOH} - \mathrm{SOH} - \mathrm{AOH}}{\mathrm{PH} - \mathrm{SOH} - \mathrm{AOH}} \tag{11}$$

[European formula]

where

PH	Period Hours (one year—8760 h),
FOF	Forced Outage Hours,
SOH	Scheduled Outage Hours, and
AOH	Administrative Outage Hours.

This formula, seen frequently in European bid specs, is variously called "Forced Outage Availability" or "Running Availability" or just plain "Availability." It is the truest measure of the time-based probability for avoidance of forced outages and it is fully suitable as a warranty measure for units of any service application whether peaking or continuous service. The "Administrative Outage Hours" (AOH) category admirably covers any number of "stop-the-clock" provisions for outage events that should not be charged against the equipment. To continue the example: If the machine with 175 forced outage hours and 100 service hours also had 200 scheduled outage hours plus 20 administrative outage hours, its annual "running reliability" would be 97.95%. The European formula also has alternate forms that sometime appear in bid specifications

$$\mathrm{RR} = \frac{\mathrm{SH} + \mathrm{RSH}}{\mathrm{SH} + \mathrm{RSH} + \mathrm{FOH}} \quad \text{[European Version 2]} \tag{12}$$

where SH = In Service Hours (fired hours), RSH = Reserve Shutdown Hours, and FOH = Forced Outage Hours, and also

$$\mathrm{RR} = \frac{\text{Available Hours}}{\text{Available Hours} + \text{FOH}} \quad \text{[European Vers. 3]}. \tag{13}$$

E. $\text{Reliability} = \frac{\mathrm{MTBF}}{\mathrm{MTBF} + \mathrm{MTTR}}$ [textbook formula](14)

where MTBF = Mean Time Between Failures, and MTTR = Mean Time To Repair. This classical textbook formula [2] is used in the EPRI UNIRAM program and is often applied to components or subsystems. It originated as a measurement of reliability for systems that were expected to be in continuous service such as telephone and communications systems. If the MTBF is measured in period time (clock/calendar hours), the result numerically approximates the GT traditional formula (4). If the MTBF is measured in service hours, the result numerically approximates the utility FOR formula (9). This formula and the terms MTBF and MTTR are more often tools of the reliability engineer than the power plant operator. There are at least two reasons why this is not a good formula, or measure, for warranty purposes: 1) The terms MTBF and

MTTR are derived, rather than directly-measured values, and 2) it tends to be overly sensitive to event rate.

F. RR = (1 - CFOR) [corrected FOR formula] (15)

where

$$\text{CFOR} = \text{Corrected Forced Outage Rate}$$

$$\text{CFOR} = \frac{(\text{FOH})(\text{DDF})}{(\text{FOH})(\text{DDF}) + \text{SH}} \quad (16)$$

and

FOH Forced Outage Hours,
DDF Daily Duty Factor,
(Fired Hours per Start)/24, and
SH Service Hours.

The Corrected Forced Outage Rate (CFOR) is an attempt to more fairly apply the concept of Forced Outage Rate (FOR) to low usage situations such as "peaking" duty. See [3] for a complete discussion of this approach. This formula is purported to be an applied approximation of a four-state Markov model (with which some utilities are experimenting), and through the Daily Duty Factor (DDF) it recognizes that much of the forced outage repair time is accrued when the unit is not in demand (and maybe not even being worked on). For the original example machine of 175 forced outage hours and 100 service hours, we might ascertain that the average fired hours per start is 4.0. That gives a daily duty factor of 0.167, a CFOR of 6.8%, and a reliability of 93.2%. Not as optically pleasing a number as the GT and European formulas produce but tremendously better than the 36.4% associated with the uncorrected forced outage rate formula (9). This is a fair reliability warranty measurement for peaking units but it depends on a derived (or arbitrary) correction factor. It has seen little exposure and even less acceptance.

G. $\text{RR} = e^{-(\lambda)t}$ [mission reliability] (17)

where e = the base of the natural log (2.71828), λ = the failure rate in events per hour which is also equivalent to 1/MTBF, and t = mission time in hours. Mission reliability is a classical reliability measurement tool and represents the probability that a mission of time (t) will be successfully completed once started. Mission reliability is extensively used in military and aerospace design and is most applicable to continuously functioning components or systems where there is no opportunity for in-service repair. Unlike all of the foregoing reliability definitions (or formulas), mission reliability is oblivious to the repair or outage time. But it is still useful to estimate the probability of completing a run or to predict component failures. If the "example" machine has a 250-service-hour MTBF in peaking service, then the probability of completing a 4-h run is 98.4%, and that would be called the mission reliability. Mission reliability is an excellent design or system planning tool but a poor warranty measurement device.

H. $\text{RR} = 1 - \dfrac{\text{SF} + \text{FOE}}{\text{SF} + \text{SS}}$ [P.R. Index-1] (18)

where SF = Starting Failures, FOE = Forced Outage Events (from the running state), and SS = Starting Successes. The "Peaking Reliability Index" (PRI) is a fairly new approach that is quite attractive as a single, simple, fair, and overall measure for peaking or cycling duty units. It is strictly an "events" based extension of starting reliability that views the probability of not only starting, but completing a run. The simplicity of the measurement offers strong argument, particularly for warranty purposes. In the continuing example: As the peaking "example" machine sees 25 successful starts and 100 service hours, it likely endured one starting failure and maybe one forced outage event (a trip) from the running condition. The corresponding PRI Reliability is easily calculated at 92.3%.

I. $\text{RR} = 1 - \dfrac{\text{UOE}}{\text{SF} + \text{SS}}$ [P.R. Index-2] (19)

where

UOE Unplanned Outage Events,
SF Starting Failures, and
SS Starting Successes.

This alternate "Peaking Reliability Index" is a little broader than the first version, (18) above, in that it relates all unplanned planned outage events to the number of attempted runs. It is an excellent general measure of the freedom from unplanned outages. As the peaking "example" machine sees 25 successful starts, 100 service hours, one starting failure, one forced outage (trip) event, and one unplanned maintenance outage repair event accomplished during a period of no demand, the corresponding PRI-2 Reliability is calculated at 88.5%.

J. $\text{RR} = (\text{P}_{\text{avail}})(\text{SR})(\text{P}_{\text{mission}})$ [demand rel.] (20)

where P_{avail} = probability of being available using the European formula (11), SR = Starting Reliability, and $\text{P}_{\text{mission}}$ = probability of completing the mission using the Mission Reliability formula (17). This demand reliability formula is receiving increased usage by utilities as a planning tool for peaking and daily cycling units. See [4], which is both specific and encompassing in nature, and is an excellent *collective* measure for most generating units. It has a disadvantage of producing poor appearing numbers for units that target for very long continuous runs (thousands of hours). It is also somewhat complex for implementation as a warranty measurement. If the base case "example" machine has a starting reliability of 96%, then the demand reliability is (0.9795)(0.96)(0.984) = 92.5%. This is perhaps the best measure of the probability that a generating unit in peaking service will provide electricity for a period of demand.

The dilemma of the existence and usage of so many formulas is tacitly acknowledged by the two leading USA norms, ANSI/IEEE Std 762 and NERC GADS, in that neither attempts to provide a specific mathematical formula for the terms reliability or running reliability.

The author has provided his rating of the applicability of the different running reliability formulas for use in different warranty and engineering situations (see Fig. 5). The basic criteria for the ratings on warranty measurements are as follows:

1) The measure should have a tangible feeling; that is, it should be a simple measure calculated directly from counting hours and/or events.

	Formula for Running Reliability	Warranty Measurements: Peaking < 20 FH/start	Mid-Range <6,000 FH/year	Base >6,000 FH/year	Reliab. Engrg. & Systems Planning
A. Trad. GT	1 - FOF	Fair	Good	$\boxed{\text{V.G.}}$	$\boxed{\text{V.G.}}$
B. "UOF"	1 - UOF	Fair	Good	$\boxed{\text{V.G.}}$	$\boxed{\text{V.G.}}$
C. Utility FOR	1 - FOR	V.P.	Poor	Good	Limited
D. European	$\frac{SH + RSH}{SH + RSH + FOH}$	$\boxed{\text{V.G.}}$	$\boxed{\text{V.G.}}$	$\boxed{\text{V.G.}}$	Fair
E. Textbook	$\frac{MTBF}{MTBF + MTTR}$	V.P.	Poor	Fair	Limited
F. Corrected	1 - CFOR	Fair	Poor	N.A.	Limited
G. Mission	$e^{-(lambda)t}$	V.P.	V.P.	Poor	$\boxed{\text{V.G.}}$
H. P.R.I.-1	$1 - \frac{SF + FOE}{SF + SS}$	$\boxed{\text{V.G.}}$	Fair	Poor	Fair
I. P.R.I.-2	$1 - \frac{UOE}{SF + SS}$	$\boxed{\text{V.G.}}$	Fair	Poor	Fair
J. Demand	$(P_{avail})(SR)(P_{miss})$	V.P.	V.P.	V.P.	$\boxed{\text{V.G.}}$

Abbreviations:

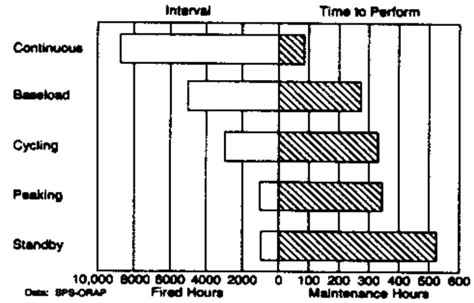
V.G. = Very Good
V.P. = Very Poor
N.A. = Not Applicable

Fig. 5.

2) The measure should closely describe the probability of the machine being able to deliver service when it is expected to be in service.
3) There should be zero or minimum dependence on arbitrary or approximated factors.
4) The resulting number should have political and emotional acceptability; i.e., if it is a measure of reliability, it should read above 90%.

Warranties on running reliability are reasonable for all service applications from peaking to continuous duty if the proper formula is selected. Warranty structuring for running reliability guarantees is concerned with good recordkeeping and careful outage management (including correct categorization of the forced outage events and the elements of restoration time). Furthermore, it is good to decide when writing the warranty terms whether the warranty is basically intended to nominally cover the equipment only or the equipment plus the user's and/or manufacturer's service system. Most manufacturers are not keen to pay liquidated damages for downtime hours where the user applied his limited maintenance resources to other projects because of other priorities.

Appendix B includes a generic sample warranty statement (plus qualifying clauses) for a running reliability warranty based on the "European" formula.



SERVICE APPLICATION

Duty	Service Factor %	FH per Start	# of Insp.	Insp. Interval	Outage Hours
Continuous	80-100	>120	28	8675	88
Base Load	30-80	>60	178	5048	276
Cycling	10-50	10-20	160	3206	339
Peaking	2-10	3-10	120	1072	355
Standby	0-2	<4	2	1073	529

Fig. 6.

VI. Maintenance Intensity

The time-based measurements of availability and running reliability generally count the grand total elapsed outage hours without differentiating actual applied repair time from unapplied time or planned tasks from ad hoc inspection activities. Some critical peaking or cycling units are overly maintained. And some minor two-hour repair tasks are logged at over a hundred outage hours because of low maintenance priority and idle time. Waiting time for replacement parts can have an even more serious effect. Availability can become more a measure of the service system than the inherent disposition of the equipment to perform. In reviewing ORAP data for many machines, it becomes obvious that the maintenance intensity effect is a very significant factor, it is driven by the operators's need for the equipment and it can be correlated to the service application. Fig. 6 exquisitely illustrates this effect.

The combustion inspection is a fairly standard gas turbine maintenance inspection, yet some operators perform it more often than others, and the *average* elapsed period hours taken to accomplish this inspection vary by 6 to 1 across the service application categories! From all 488 inspections the average amount of hours to complete is 306. But is the "average" representative? How about the manufacturer's instruction book? Reference [5] estimates 12 eight-hour shifts (or as little as 96 clock/period hours) for the MS7001 combustion inspection. The data indicate that this is reasonably demonstrated by the continuous duty units where the need and maintenance intensity are high, where three-shift maintenance is often employed, and where an offline, "replace-then-repair," parts correction technique is applied.

Maintenance intensity effect is such a significant factor that it must be addressed with every time-based availability or running reliability warranty situation. All maintenance may be performed by the equipment supplier, or agreement reached on specific maintenance conduct, or a warranty qualification set up to exclude excessive inspection events and excessive waiting time. The additional subclassifications of outage time necessitate more detailed recordkeeping and a separate set of warranty performance measurements that will be numerically different from the normal ORAP or NERC GADS measurements. Two (or even three) "sets of books" will have to be kept.

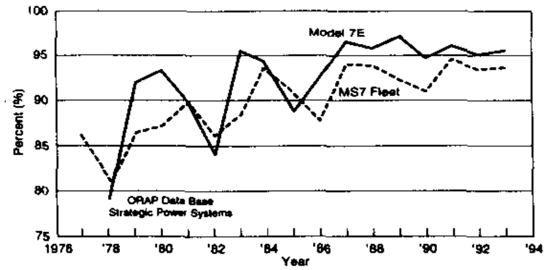


Fig. 7. Availability, MS7001 domestic (USA) units.

VII. Availability

Availability is the popular measure of the *portion of time* that a unit is available to serve load because it is not on forced outage, maintenance outage, or planned outage. NERC GADS, ANSI/IEEE Std 762-1987 and ORAP recognize Availability as a key performance index and more specifically call it the "Availability Factor" (AF).

$$\text{Availability Factor} = \frac{\text{Available Hours}}{\text{Period Hours}} \tag{21}$$

where

$$\text{Available Hours (AH)} = \text{PH} - \text{FOH} - \text{MOH} - \text{POH}$$

and

PH Period Hours (one year—8760 h),
FOH Forced Outage Hours,
MOH (unplanned) Maintenance Outage Hours, and
POH Planned Outage Hours scheduled well in advance).

Sometimes the "availability" label is applied to a more limited measurement, one that removes scheduled outage hours or some other element. These situations have been addressed in Section V. And when "availability" becomes concerned with capacity levels or deratings or plant-level ratings (as it should with multi-shaft combined cycle units) it belongs to Section VIII.

It should also be pointed out that while availability is an excellent measure for high usage machines, it is a relatively poor measure to be applied to low usage machines. In periods of low equipment need there is usually little incentive to accomplish scheduled or even essential maintenance in an expeditious manner. The inevitable stretch of outage time accrues unfavorably to the measurement. If the service application is low usage peaking service, it is advisable to consider a more appropriate running reliability guarantee along the lines of the "European" formula (11) or the "Peaking Reliability Indexes" (18), (19) or perhaps just a Starting Reliability guarantee.

The structuring of availability warranties is similar to the structuring of running reliability warranties. For both, the focus is on the management of outage time, but for availability there must also be some control over the conduct of planned maintenance. And, in recognition of the fact that there will be nonchargeable outage time, the warranty version of the availability formula is preferably written as follows:

$$\text{Availability of Warranty} = \frac{\text{AH}}{\text{PH} - \text{AOH}} \tag{22}$$

where Available Hours (AH) also equals PH − FOH − MOH − POH − AOH and

PH Period Hours (one year—8760 h),
FOH Forced Outage Hours,
MOH (unplanned) Maintenance Outage Hours,
POH Planned Outage Hours (scheduled well in advance), and
AOH Administrative Outage Hours (nonchargeable hours).

Fig. 7 traces the average annual availability performance of the domestic (USA) MS7001E/EA units participating in the SPS-ORAP data system. Appendix C includes a generic sample of an availability warranty statement with qualifying terms.

VIII. Equivalent Availability

When the term "Equivalent" is applied to availability or reliability it could mean several things. Under IEEE Std 762-1987 and NERC GADS it extends the concept of availability or reliability to account for varying capacity levels and in effect becomes a measure of *energy production availability*. This is the context advocated by this author. In other uses, the term "equivalent" is sometimes associated with an approximation type measurement that may have nothing to do with capacity. Sometimes, the term "equivalent" might be used to distinguish the subsystem level or component level from the full system generation level. For example, the reliability performance of a problematic limit switch might be described in terms of its Equivalent Forced Outage Rate (EFOR) which was deduced from its MTTR divided by its (MTTR + MTBF). This paper, with its focus on warranty conditions, will look at three types (or levels) of "system" equivalent availability measurements which increasingly accommodate the capacity element.

A. *Equivalent Availability (EA)—Level 1 "Block Method"*

The SPS-ORAP system has for many years been measuring the equivalent availability of combined cycle plants by merely extending the traditional time-based availability measurements to the full (multi-unit) plant. If one gas turbine of a four-unit combined cycle plant is unavailable, the plant may still be operated at about 3/4 capacity. If only the steam turbine is unavailable, and there are provisions (e.g., HRSG bypass stacks) for operating the gas turbines simple cycle, then about 2/3 of the plant capacity is available. During these periods

of partial equipment unavailability the plant is respectively considered to be at 75% or 66.7% equivalent availability. This measurement system is fully described by [6]. By this measurement method, each major generating block is treated as being either available or not available to contribute a pre-established percentage of the plant's output. This block method of equivalent availability measurement can also be calculated using the NERC and IEEE suggested procedures outlined later.

The IEEE Std 762-1987 procedure for calculating the Equivalent Availability Factor (EAF) first establishes the normal time-based availability factor then provides a deduct in the form of equivalent derated hours for operation at derated capacity levels.

$$\text{EAF} = \frac{\text{available hours} - \text{equiv. derated hours}}{\text{period hours}} \qquad (23)$$

where

Available Hours

$$(\text{AH}) = \text{PH} - \text{FOH} - \text{MOH} - \text{POH}$$

Equiv. Derated Hours

$$(\text{EDH}) = \text{EUDH} + \text{EPDH} + \text{ESEDH}$$

and

PH	Period Hours (one year – 8760 h),
FOH	Forced Outage Hours,
MOH	unplanned Maintenance Outage Hours,
POH	Planned Outage Hours (scheduled well in advance),
EUDH	Equivalent Unplanned Derated Hours,
EPDH	Equivalent Planned Derated Hours, and
ESEDH	Equivalent Seasonal Derated Hours.

The Equivalent Derated Hours are determined by multiplying the derated operating time (hours) by the percentage of derating. If a four-unit combined cycle plant experienced unplanned unavailability of one gas turbine for 100 period (clock-time) hours, it is treated as a 25% "block" derating of the plant. For calculation purposes the *plant* available hours are still 100 hours (100%) but there would be the accumulation of (0.25) × (100 h) = 25 equivalent unplanned derated hours (100 AH – 25 EUDH)/100 PH = 75% EAF. When the equipment capacity is limited, all hours are derated including not only the service hours, but also the reserve shutdown hours. Seasonal derated hours, as defined by IEEE and NERC and discussed later, are excluded or set to zero in the block method.

B. Equivalent Availability—Level 2 "Proportional Block Derating"

A second example illustrates the "proportional" derating method which goes beyond the previous block method by considering deratings due to partial equipment failures. If another gas turbine generator in the same four-unit combined cycle plant had a generator rotor heating problem that prescribed a limit on output power to 92% of its rated capability for a period of 1000 h, then that gas turbine generating set would be operating with an 8% shortfall of capacity. By the proportional derating method, the *plant* would accumulate (0.08)(0.25)(1000) = 20 equivalent planned derated hours for the 1000 period hours of this generator shortfall. These 20 EPDH would not have been counted under the previous block derating method, but here at level 2 they are counted together with the other equivalent derated hours.

Using the Level 2 Proportional Block Derating Method, the plant is considered 100% available except when equipment failure reduces generating capacity. Then the amount of equivalent derating is established based upon engineering logic and negotiation. Accurately measuring the true amount of capacity shortfall is difficult as will become evident in the discussion of level 3 EAF. (Note: Appendix D provides a sample equivalent availability warranty based on the proportional block derating method).

C. Equivalent Availability—Level 3 "Full Energy Measurement"

The IEEE and NERC standards strive for a good measure of energy availability but have not fully addressed the significant (and nonfailure) factors influencing gas turbine output power levels such as:

- *Ambient Climatic Conditions:* Temperature, barometric pressure, and humidity can cause gas turbine output capability to vary by 10% or more in a 24-h period without any equipment failures or faults chargeable to unreliability. And seasonal variations can be worth as much as 30% change in output power capability.
- *Compressor and Turbine Cleanliness Levels:* The state of cleanliness of the gas turbine's compressor and turbine sections can impact output capability by up 10% in extreme cases. This is a site environment/maintenance issue; it is not a reliability issue, but should it be counted as equivalent unavailability?
- *Compressor and Turbine Degradation:* Aging and wear cause clearances to increase and flow path surfaces to roughen, ultimately decreasing output capability by 5% or more in a normally unrecoverable manner. This is not usually categorized as equipment failure but some would have it be counted as equivalent unavailability.

So, the measure of equivalent availability, on a full energy production capability measurement basis, is not just one of reliability or equipment failure, but also how to deal with the other major performance factors. An equivalent availability guarantee especially needs a very clear and explicit set of warranty terms and conditions. Despite the complexity, the full energy measurement basis of EAF is exactly what some independent power producers and nonutility generators are seeking in order to insure the profitability of their ventures.

One technical solution suggested by the author is to utilize a small computer model to first calculate the theoretical "new-and clean" performance on an average hourly basis from the manufacturer's plant performance algorithms. Then, *actual hourly output capability* would be calculated by subtracting a cleanliness (fouling) correction, a degradation correction and an equipment failure correction (derating). Negotiation would determine which corrections would be included in the

TABLE I

Number of Start Attempts	85% Confidence Levels on 95% inherent SR to Favor or Protect Seller	Buyer
20	90	Not Possible
50	92	98
100	93	97
400	93.75	96.0
1000	94.3	95.7

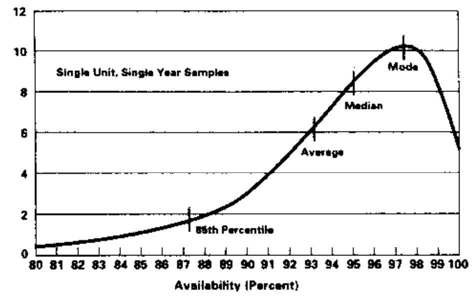


Fig. 8. Typical availability distribution. Percent samples per percent availability.

EAF measurement. The value of each of the corrections is determined by regularly pressing the generating machinery to maximum operating level and recording the actual output power. Since most of these measurements would not have equipment failure deratings in effect, it is possible to determine the average deterioration of performance due to long term degradation, the rate of deterioration due to fouling, and the amount of recovery associated with cleaning. The derating due to equipment failure can also be tested, or even measured on an hourly basis. Those corrections that had been agreed to be included in the EAF measurement would then be integrated to equivalent derated hours for use in the EAF equation (23).

Unfortunately, several known projects have been committed to EAF guaranties without preestablishing the measurement system, measurement formulas, or rules. When the equipment finally enters commercial operation, the dilemma of the measurement system becomes clear and the warranties have defaulted to compromise positions such as negotiated seasonal (monthly or quarterly) production quotas with associated bonus/penalty conditions. EAF has become the percent achievement of the quota and it has sometimes exceeded 100% (defying all traditional reliability theory). Even the variance of the weather has been passed back to the equipment manufacturer! When IEEE and NERC standards invoke the "Seasonal Derating" term for gas turbines, it effectively offers the same compromise position and the same problems for gas turbine power plants.

Thinking broadly about all equivalent availability guarantees, they can be applied for simple cycle gas turbines up through the most complex combined cycle plants, but the measurement system and warranty structure must be very carefully thought out and agreed upon between all parties to the contract. The simple time-based measures of availability and block method EAF are often more appropriate, and more easily measured and preferred for their simplicity. And like availability, the EAF is a good measure for high usage plants and a poor (undesirable) measure for low usage machines.

In recognition of the fact that there will be nonchargeable outage time, the warranty version of the equivalent availability formula is suggested as follows:

$$\text{EAF Under Warranty} = \frac{\text{AH} - \text{EDH}}{\text{PH} - \text{AOH}} \tag{24}$$

where Available Hours (AH) = PH − FOH − MOH − POH − AOH and Equivalent Derated Hours (EDH) = EUDH + EPDH + ESEDH and

PH	Period Hours (one year − 8760 h),
FOH	Forced Outage Hours,
MOH	unplanned Maintenance Outage Hours,
POH	Planned Outage Hours (scheduled well in advance),
AOH	Administrative Outage Hours,
EUDH	Equivalent Unplanned Derated Hours,
EPDH	Equivalent Planned Derated Hours, and
ESEDH	Equivalent Seasonal Derated Hours.

IX. Measurement Uncertainty

When money or reputation are at stake, it is important that the measurement system be both accurate and representative. The accuracy of the data is accomplished through a "rigorous and explicit" logging system that identifies the nature of each operating event (and outage) together with the starting and stopping times to the nearest minute or tenth of an hour. Representativeness of the data is a little tougher to deal with because of the randomness of occurrence of failure events and the widely distributed spacing of planned maintenance events.

The term "representativeness" is used here to relate the actual measured value to the inherent long-term operating norm of the equipment. This was partially addressed under starting reliability with reference to the number of start attempts required in the measurement to be statistically representative of the real, inherent mean. Table I illustrates the 85% confidence band around 95% inherent starting reliability to protect seller and buyer.

A similar situation of randomness exists with Running Reliability and Availability measurements. The statistician will advise that at least 25 to 30 unplanned outage events are needed in the measurement set in order for the MTTR and MTBF to be considered representative of the inherent performance level of the equipment. Once again it is appropriate to average multiple units and even multiple years of operating data.

Fig. 8 shows the smoothed probability distribution function of a sample set of availability data for simple cycle gas turbine generating sets taken on a single unit, single year basis. It nicely shows the "mode" units which the sales personnel love

to tout: the fleet "average" (mean) data which is commonly shown as the collective performance statistic, and then a couple of distribution statistics. To the author, the "median" machine performance is a better indicator of expectations for single units than the "average" fleet performance, but the important number for warranty situations should be somewhere near the 85th percentile. At that point there is about 85% probability of successful achievement and only 15% probability of failure. By averaging multiple units and multiple years of data in the measurement, the gap between the 85th percentile and the "average" can be significantly closed. Bonus/penalty arrangements can also drive the guarantee point closer to the "average."

It should therefore be recognized by all parties that guarantee points will normally be more pessimistic than fleet average performance, median machine performance or the mode example machines.

X. Warranty Terms

A contractual warranty requires not only a measurement formula, definition of factors, and a guarantee number, but a set of terms to qualify the environment. Here is a reasonably full house of terms to choose from:

For all Reliability Warranties:

1) The reliability warranty is fully separate and independent from the equipment warranty. The warranties may have separate starting times, ending times, and commercial remedies.
2) A rigorous and explicit operating log shall be maintained from which the performance under warranty is to be determined. The log shall clearly identify the time, the cause, the capacity reduction, the amount of waiting time and/or idle maintenance time associated with each and every outage event and be periodically reviewed and jointly certified with the warrantor's technical representative.
3) With the seller's assistance and concurrence, the equipment operator shall have a documented maintenance program which covers scheduled maintenance plans, a work schedule agreement, and well planned replacement parts support.
4) The equipment shall be operated and maintained in accordance with the suppliers' recommended procedures with particular attention to maintenance inspection intervals and preventative maintenance activities.
5) A two-week (minimum) reliability demonstration period including no less than 5 start-stop cycles, 50 fired hours and mutually acceptable results shall precede the warranty measurement period.
6) Outage hours or events not directly chargeable to failure of equipment furnished under the contract shall not be chargeable to the warranty.

Additional Clauses for Starting Reliability Warranties:

7) Test starts and failures to start from equipment not furnished by the seller shall not be counted as start attempts, failures, or successes.
8) As a general assurance of readiness: If a unit has not experienced a successful start during the prior thirty days, then the start attempt shall be considered as a nonwarranty-qualifying "test start" and shall not be counted.
9) Measurement blocks of at least 500 unit start attempts are desired to ensure that the measured SR is statistically representative of the inherent (true) SR. Where liquidated damages without bonus provisions are associated with the measurement of SR, and the measurement block has less than 500 start attempts, then a measurement tolerance band shall be inserted between the guarantee point and the point of damages assessment. The measurement tolerance shall consider the actual number of start attempts and relate the measured SR to guaranteed SR with 85% statistical confidence.

Additional Clauses for Running Reliability, Availability and Equivalent Availability Warranties (as Applicable):

10) For purposes of the warranty measurement: Inspections, maintenance, and repair shall be gauged on a high priority, high need basis. To achieve this, waiting time and inactive maintenance time in excess of four hours per outage event shall be charged to administrative outage hours and not charged against the warranty.
11) Equipment outages shall be considered on a "block" basis. Each individual major piece of equipment (gas turbine, generator, HRSG, or steam turbine) shall be treated as either available or unavailable at any point in time. Equivalent outage hours shall be accumulated for "block" outages but not for reductions in capacity of the individual major pieces of equipment.
12) Planned outage inspections shall be performed on a "replace then repair" basis with all needed replacement parts on hand at the start of the inspection. NDE inspections, repairs and cleaning up of removed components are to be done separately from the outage/inspection activities.
13) Planning for outage inspections shall address all major equipment on a concurrent maintenance basis to be consistent with the basis of formulation of the guarantee level. If concurrent maintenance cannot be practiced, then the nonconcurrent planned outage hours for nongas turbine equipment shall not be chargeable as either outage hours or period hours, but as administrative outage hours.
14) Whereas seasonal deratings (due to ambient conditions) do not constitute any form of equipment failure, the Equivalent Seasonal Derated Hours (ESEDH) shall be set to zero and not factored into the measurement.

XI. Conclusion

In the author's experience of writing and negotiating reliability warranties, there was much new ground to break. There are also several major steps in the process of reaching an equitable warranty structure:

Step 1: Recognize the value of reliability to the point that it must be insured during the contracting process.

Step 2: Realize the fact that there are no commonly accepted standards and definitions that can be directly and solely used to establish the warranty measurement.

The current "standards," including IEEE Std 762, NERC GADS, ORAP, and the German VDEW, take a total plant operation approach. There are no provisions for dealing with nonchargeable outages or for separating nominal equipment restoration aspects from service system aspects.

Different site applications require different treatment. Single unit peakers operating 200 fired hours per year should be under warranty by different measurements than base-loaded, multi-unit, combined cycle plants.

Step 3: Reconcile the "real-life" warranty consideration factors and determination of the appropriate measurement for the specific application.

Part of this process is to "rough in" the qualifications concerning which outage events or hours shall be chargeable to the warranty, or fully excluded from the warranty or handled on a "stop-the-clock" basis. To aid this process, Appendix E contains a Worksheet for Allocation of Outage Hours.

Step 4: Capture the ideas of step 3 in suitable contract language.

Step 5: Implement the measuring system with log sheet forms (hopefully computerized) to semi-automatically track each machine covered by the warranty. The degree of detail or categorization afforded by the log shall support multiple reporting needs including the qualified warranty performance, NERC GADS reporting data, traditional performance measures (e.g., ORAP) and engineering-desired events data.

As reliability gets more widely and properly measured, so will its value become more appreciated and sought after on a tangible basis.

APPENDIX A

Starting Reliability Guarantee

[Project/Contract Title]

[Date]

A. Starting Reliability Statement

The average Starting Reliability of the [Model/Type] gas turbine-generator units furnished under this contract is guaranteed to be not less than [96.7%] over the warranty measurement period as measured in accordance with the definitions and concepts of ANSI/IEEE Std.762-1987. The warranty measurement period for each machine shall commence on the date of first commercial operation and expire [three years] from that date.

B. Starting Reliability Warranty Context

1. The ANSI/IEEE Std.762-1987 provides definitions and a formula for Starting Reliability that allow for the fact that not all failures-to-start or incomplete start attempts are chargeable to equipment failure or to the warranty. Starting Reliability is to be measured by the IEEE formula as follows:

$$\textbf{Starting Reliability} = \frac{SS}{SS + SF}$$

Where:

SS = Chargeable Starting Successes
SF = Chargeable Starting Failures

And:

A Qualifying Starting Attempt is the action intended to bring a unit from shutdown to the in-service state under conditions that qualify for inclusion in the warranty. Repeated initiations of the starting sequence within the allowable specified starting time period or without accomplishing corrective repairs are counted as a single attempt.

A Chargeable Starting Success (SS) is the occurrence of bringing a unit through a qualifying starting attempt to the in-service state within a specified period, as evidenced by maintained closure of the generator breaker to the system.

A Chargeable Starting Failure (SF) is the inability to bring a unit through a qualifying starting attempt to the in-service state within a specified period for failure reasons chargeable to the warranty. Repeated failures within the specified starting period are to be counted as a single starting failure.

2. On an annual basis or at each accumulation of 500 qualifying start attempts (whichever is greater), the Starting Reliability shall be calculated collectively as a single average measurement of all of the contract units that are within the warranty measurement period. If the calculated average Starting Reliability falls below the guarantee level, it shall be remedied in accordance with the terms set forth [in the Commercial section].

If the measurement must be made with an accumulation of less than 500 start attempts, the statistical measurement uncertainty shall be recognized by providing an allowance from the guarantee level. The Measurement Uncertainty Allowance shall adjust the point of damages initiation based on the cumulative binomial probability function and the actual number of start attempts to assure with 75% confidence that the indicated (measured) shortfall is due to equipment deficiency rather than the random nature of failure occurrences.

3. A rigorous and explicit operating log shall be maintained from which the starting reliability measurement is to be determined. The log shall be periodically reviewed and jointly certified with a [Supplier] technical representative.

4. Test Starts and failures to start from equipment not furnished under this contract by [Supplier] shall not be counted as start attempts, failures or successes.

5. As a general assurance of readiness; if a unit has not experienced a successful start during the prior thirty (30) days, then the start attempt shall be considered as a non-warranty "test start" and shall not be counted.

6. Procedural errors that do not constitute equipment failure involving repair shall not be counted as failures-to-start.

7. The units shall be operated within the design conditions specified in the contract and maintained in accordance with [Supplier] recommended procedures with particular attention to maintenance inspection intervals and preventative maintenance activities.

APPENDIX B
Running Reliability Guarantee
[Project/Contract Title]
[Date]

A. Running Reliability Statement

Running Reliability shall be guaranteed in terms of the ratio of actual available hours to planned available hours. The Running Reliability for the gas turbine-generator units furnished under this contract is guaranteed to average not less than [97.2%] over the warranty measurement period. The measurement period shall commence on successful completion of the two-week reliability readiness test. It shall expire [two years] after the date of first commercial operation.

B. Running Reliability Warranty Context

1. In recognition of the fact that there will be non-chargeable outage time, the warranty version of the running reliability formula shall be as follows:

$$\textbf{Running Reliability} = \frac{AH}{PH - POH - AOH}$$

where: Available Hours (AH) also equals
PH-FOH-MOH-POH-AOH

and: PH = Period Hours (usually one year - 8760 hours)
FOH = Forced Outage Hours
MOH = (unplanned) Maintenance Outage Hours
POH = Planned Outage Hours (scheduled well in advance)
AOH = Administrative Outage Hours (non-chargeable)

and: The above terms (except AOH) are more fully conceptualized and defined by ANSI/IEEE Std 762-1987

2. A rigorous and explicit operating log shall be maintained from which the Running Reliability measurement is to be determined. The log shall clearly identify the cause and the amount of waiting time and/or idle maintenance time associated with each and every outage event and be periodically reviewed and jointly certified with a [Supplier] technical representative.

3. With [Supplier] assistance and concurrence, the equipment operator shall have a documented maintenance program which covers scheduled maintenance plans, a work schedule agreement and well-planned replacement parts support.

4. The unit shall be operated and maintained in accordance with [Supplier] recommended procedures with particular attention to maintenance inspection intervals and preventative maintenance activities.

5. A two-week (minimum) reliability demonstration period including no less than 5 start-stop cycles, 50 fired hours and mutually acceptable results shall precede the Running Reliability warranty measurement period.

6. For purposes of the warranty measurement; inspections, maintenance and repair shall be gauged on a high priority, high need basis. To achieve this, waiting time and inactive maintenance time in excess of four hours per outage event shall be considered as Administrative Outage Hours (AOH). As such, they shall have "stop-the-clock" treatment and effectively not be counted as outage hours, derated hours or included in the period hours base.

7. Outage hours associated with the [Supplier] furnished equipment but not directly chargeable to equipment failure shall be considered as Administrative Outage Hours (AOH).

8. Operator shall operate the gas turbine unit within the design conditions specified in the contract.

APPENDIX C

Availability Guarantee

[Project/Contract Title]

[Date]

A. Availability Statement

Availability shall be guaranteed in terms of the Availability Factor as described in the definitions and concepts of ANSI/IEEE Std 762-1987. The average Availability Factor for the [#/model] gas turbines generator sets furnished under this contract is guaranteed to average not less than [95]% over the warranty measurement period. The measurement period shall commence on successful completion of the two-week reliability readiness test. It shall expire [three] years after the date of first commercial operation.

B. Availability Warranty Context

1. In recognition of the fact that there will be non-chargeable outage time, the warranty version of the availability formula shall be as follows:

$$\textbf{Warranted Availability Factor} = \frac{\textbf{AH}}{\textbf{PH - AOH}}$$

where: Available Hours (AH) also equals PH-FOH-MOH-POH-AOH

and:
- PH = Period Hours (usually one year - 8760 hours)
- FOH = Forced Outage Hours
- MOH = (unplanned) Maintenance Outage Hours
- POH = Planned Outage Hours (scheduled well in advance)
- AOH = Administrative Outage Hours (non-chargeable)

2. A rigorous and explicit operating log shall be maintained from which the Availability measurement is to be determined. The log shall clearly identify the cause and the amount of waiting time and/or idle maintenance time associated with each and every outage event and be periodically reviewed and jointly certified with a [Supplier] technical representative.

3. On an annual basis the Availability Factor shall be calculated collectively as a single average measurement of all the contract units that are within the availability warranty measurement period. If the calculated average Availability Factor falls below the guarantee level, it shall be remedied in accordance with the terms set forth in the [Commercial] agreements.

4. With [Supplier] assistance and concurrence, the equipment operator shall have a documented maintenance program which covers scheduled maintenance plans, a work schedule agreement and well-planned replacement parts support.

5. The unit shall be operated and maintained in accordance with [Supplier] recommended procedures with particular attention to maintenance inspection intervals and preventative maintenance activities.

6. A two-week (minimum) reliability demonstration period including no less than 5 start-stop cycles, 50 fired hours and mutually acceptable results shall precede the availability warranty measurement period.

7. For purposes of the warranty measurement; inspections, maintenance and repair shall be gauged on a high priority, high need basis. To achieve this, waiting time and inactive maintenance time in excess of four hours per outage event shall be considered as Administrative Outage Hours (AOH). As such, they shall have "stop-the-clock" treatment and effectively not be counted as outage hours, derated hours or included in the period hours base.

8. Outage hours associated with the [Supplier] furnished equipment but not directly chargeable to equipment failure shall be considered as Administrative Outage Hours (AOH).

9. Planned outage inspections shall be performed on a "replace then repair" basis with all needed replacement parts on hand at the start of the inspection. NDE inspections, repairs and cleaning up of removed components is to be done separately from the outage/ inspection activities.

10. Operator shall operate the gas turbine unit within the design conditions specified in the contract.

APPENDIX D
Equivalent Availability Guarantee
(Proportional Block Derating Method)
[Project/Contract Title]
[Date]

A. Availability Statement

Availability shall be guaranteed in terms of the Equivalent Availability Factor as generally described in the definitions and concepts for the ANSI/IEEE Std 762-1987. The average Equivalent Availability Factor for the contract-furnished gas turbines, generators and supporting controls and accessories is guaranteed to average not less than [90%] over the warranty measurement period. The measurement period for each generating set shall commence on successful completion of the two-week reliability readiness test. It shall expire two years after the date of first commercial operation.

B. Availability Warranty Context

1. In order to reflect capacity reductions due to equipment failures and deal with non-chargeable outage time, the warranty version of the equivalent availability formula shall be as follows:

$$\textbf{Warranted Equivalent Availability Factor} = \frac{AH - EDH}{PH - AOH}$$

where: Available Hours (AH) also equals
PH - FOH - MOH - POH - AOH by the
conventional, time-based, IEEE 762 definition

Equivalent Derated Hours (EDH) equals EUDH + EPDH calculated for periods of derating due to specific equipment failure and excluding seasonal derating and nominal degradation of performance

and: PH = Period Hours (usually one year-8760 hours)
FOH = Forced Outage Hours
MOH = (unplanned) Maintenance Outage Hours
POH = Planned Outage Hours (scheduled well in advance)
AOH = Administrative Outage Hours (non-chargeable)
EUDH = Equivalent Unplanned Derated Hours
EPDH = Equivalent Planned Derated Hours

2. A rigorous and explicit operating log shall be maintained from which the Equivalent Availability measurement is to be determined. The log shall clearly identify the cause and the amount of waiting time and/or idle maintenance time associated with each and every outage event plus all data required to calculate EDH including minimum and maximum ambient temperatures and the effective reduction in dispatchable dependable capacity. The log will be periodically reviewed and jointly certified with a [supplier] technical representative

3. The Equivalent Derated Hours (EDH) shall be calculated on a daily basis as follows:

a. For days wherein generating capacity is not limited by specific failure of contract-furnished equipment, the EDH shall be taken as zero (0).

b. For days that generating capacity is partially derated due to specific failure of the contract-furnished equipment, the EDH shall be calculated as the ratio of the capacity shortfall to the daily dependable capacity multiplied by the number of hours the derating was in effect. General degradation shall not be considered as specific failure.

For example; for each day with some capacity derating, the minimum and maximum ambient temperatures for the operating period are noted, recorded and averaged to determine the median daily operating temperature. Utilizing performance curves from the manufacturer, a "new and clean" plant capacity level is determined for that median temperature. Then that capacity is reduced by a nominal predicted degradation amount to arrive at the median daily dependable capacity. Now, because of the impact of the specific component failure, a maximum dispatchable capacity level will exist which must be rationally determined. (If the plant is fully dispatched for the full day, then the full day's generation in kWh divided by 24 hours is the maximum dispatchable capacity.) The difference between the median daily dependable capacity and the maximum dispatchable capacity is the shortfall.

The ratio of the shortfall to the median daily dependable capacity is the degree of derating. Then multiplying the degree of derating by the number of hours that the derating was in effect that day, yields the Equivalent Derated Hours.

4. With [Supplier's] assistance and concurrence, the equipment operator shall have a documented maintenance program which covers scheduled maintenance plans, a work schedule agreement and well-planned replacement parts support.

5. The unit shall be operated and maintained in accordance with [Supplier] recommended procedures with particular attention to maintenance inspection intervals and preventative maintenance activities.

6. A two-week (minimum) reliability demonstration period including no less than 5 start-stop cycles, 50 fired hours and mutually acceptable results shall precede the Equivalent Availability warranty measurement period.

7. For purposes of the warranty measurement; inspections, maintenance and repair shall be gauged on a high priority, high need basis. To achieve this, waiting time and inactive maintenance time in excess of four hours per outage event shall be considered as Administrative Outage Hours (AOH). As such, they shall have "stop-the-clock" treatment and effectively not be counted as outage hours, derated hours or included in the period hours base.

8. Outage hours associated with the [Supplier] - furnished equipment but not directly chargeable to equipment failure shall be considered as Administrative Outage Hours (AOH).

9. Planned outage inspections shall be performed on a "replace then repair" basis with all needed replacement parts on hand at the start of the inspection. NDE inspections, repairs and cleaning up of removed components is to be done separately from the outage/ inspection activities.

10. Operator shall operate the gas turbine unit within the design conditions specified in the contract.

APPENDIX E
Worksheet for Allocation of Outage Hours

A = warranty chargeable hours
B = non-chargeable "stop-the-clock" hours
C = non-chargeable fully-excluded hours

	A	B	C
Classifications by Event Cause			
Clearly covered equipment			
Forced outage	(X)		
Maintenance (delayed) outage	( )	( )	( )
Planned Outage	( )	( )	( )
Unplanned Extension of planned outage	( )	( )	( )
Non-covered equipment outages			(X)
Buyer-stipulated outage time			
Equipment modifications		( )	( )
Special tests or inspections		( )	( )
Force Majeuere events			
Flood - hurricane		(X)	
Externally caused fire		(X)	
Labor problems, strike			(X)
System problems			
Excessive frequency swings			(X)
Lack of proper (in spec.) fuel			(X)
Inadequate cooling water supply	( )	( )	( )
Site specific contract exclusion events			
Cement dust fouling of inlet		( )	( )
Planned outages for residual fuel		( )	( )
Service Interruption Outage Hours			
Waiting time or idle maintenance time in excess of (4) hours per outage event considering:	( )	( )	( )
Delays for replacement parts			
Buyer stocking responsibility	( )	( )	( )
Supplier stocking responsibility	( )	( )	( )
Carrier (transportation) mishap	( )	( )	( )
Delayed in Customs	( )	( )	( )
Delays of technical advisory service			
Notification delay	( )	( )	( )
Delayed arrival	( )	( )	( )
Unapplied crafts or labor time			
2nd shift not working	( )	( )	( )
3rd shift not working	( )	( )	( )
Weekend day or holiday	( )	( )	( )
Higher priority elsewhere	( )	( )	( )
Work stretch-out labor problem	( )	( )	( )
Necessary tools/equipment not available			
Traveling cranes or lifting gear	( )	( )	( )
Special welding equipment	( )	( )	( )
Oil conditioning equipment	( )	( )	( )
Other Considerations			
________________	( )	( )	( )
________________	( )	( )	( )
________________	( )	( )	( )
________________	( )	( )	( )
________________	( )	( )	( )

REFERENCES

IEEE Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity, ANSI/IEEE Standard 762, 1987.
S. R. Calabro, *Reliability Principles and Practices.* New York: McGraw-Hill, 1962.
P. F. Albrecht, W. D. March, and F. H. Kindle, "Gas turbines require different outage criteria," *Electrical World Mag.*, April 27, 1970.
A. K. Jenkins and J. J. Lofe, "Availability predictions for combustion turbines in peaking applications," ASME paper 89-JPGC/Pwr-4, Oct. 1989.
"Gas turbine operating and maintenance instructions," GE publication GER-3620.
S. Anchukaitus, S. Della Villa, and H. Wilson, "Combined cycle power plant—A reliability measurement approach and evaluation system," presented at the 1982 Eng. Conf. Reliability for the Electric Power Ind. (Inter-ram).

Thomas E. Ekstrom received the B.S.M.E. from Northeastern University, Boston, MA.

He has worked for over 30 years in GE's Industrial and Power Systems businesses, Schenectady, NY, as an installation engineer, applications engineer, quality systems engineer, quality manager and engineering programs manager. He is currently a Senior Gas Turbine Application Engineer, in which his work includes the reliability analysis of all GE gas turbine power plant systems that involve reliability estimates or guarantees. He evaluates and structures about 60 reliability guarantees per year. He holds two patent awards and is an author of more than 20 technical papers.

Mr. Ekstrom is a member of ASQC and a recipient of numerous GE Engineering and Management awards. He is a Registered Professional Engineer in the state of New York.

Transmission Line and Equipment Outage Data

Part I

An IEEE Survey of U.S. and Canadian
Overhead Transmission Outages at 230 kV and Above

By
R. B. Adler, S. L. Daniel, Jr., C. R. Heising,
M. G. Lauby, R. P. Ludorf, T. S. White

IEEE PES Transactions on Power Delivery
Vol. 9, No. 1, January 1994, pp. 21–39

Part 2

Frequency of Transmission Line Outages in Canada

By
Don O. Koval

Conference Record of the 1994 Industry Application's
Conference Twenty-Ninth Annual Meeting
Denver, Colorado
October 2–3, 1994
Volume III, pp. 2201–2208

Part 3

Transmission Equipment Reliability Data from
Canadian Electrical Association

By
Don O. Koval

IEEE Transactions on Industry Applications
Vol. 32, No. 6, November/December 1996, pp. 1–9

AN IEEE SURVEY OF U.S. AND CANADIAN OVERHEAD TRANSMISSION OUTAGES AT 230 KV AND ABOVE

Data Analysis Task Force, Working Group on Statistics of Line Outages,
General Systems Subcommittee, Transmission & Distribution Committee

R. B. Adler (Chairman), S. L. Daniel, Jr., C. R. Heising,
M. G. Lauby, R. P. Ludorf, T. S. White

Abstract - The Working Group on Statistics of Line Outages was formed in 1981 to develop, implement and summarize the results of a survey of design characteristics of and outage experience with overhead transmission at voltages 230kV and above. The survey, distributed in July, 1985, requested the voluntary submission of specific data on overhead lines in service within the period, 1965-1985. The purposes of the effort were twofold: to update earlier surveys (1949 and 1965), and to address a growing need for line outage data to support evolving probabilistic system models for planning and operation. Data were submitted by utilities from all nine NERC/USA reliability regions and by the Canadian Electric Association representing all of Canada. The outage data were pooled and analyzed to produce average statistics which are summarized in this paper.

Keywords - Overhead Transmission, Outage Statistics, Performance Data, Reliability Analysis.

INTRODUCTION

Since the early 1970's, there has been a growing need for transmission line outage rates and restoration times to support probabilistic models for system planning and operation. Prompted by an EPRI study of transmission outage data requirements [1], the Working Group on Statistics of Line Outages was created in 1981 to develop and implement a survey to update two earlier surveys of overhead transmission in which the IEEE took a leading role [2,3]. Reference [4] provides a description of the background and development of the new survey and of the method for its distribution to potential respondents. Work on a Transmission Outage Data Submission Guide to support the survey progressed in parallel with work on standard definitions for reporting outages of transmission facilities [5]. To the degree possible, the standard definitions were employed in the guide.

Similar to its precedents, the new survey, distributed in 1985, was intended to serve two broad objectives: to provide a snapshot of the design characteristics of overhead transmission facilities operating at 230kV and higher, and to quantify the performance of the various classes of lines on which data were submitted. The background and results in meeting the first objective are reported in [6]. The present paper reports on the second objective.

93 WM 054-7 PWRD A paper recommended and approved by the IEEE Transmission and Distribution Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1993 Winter Meeting, Columbus, OH, January 31 - February 5, 1993. Manuscript submitted September 16, 1992; made available for printing November 3, 1992.

Specific goals adopted for the 1985 survey of overhead transmission outage events were:

1. To develop generic estimates of failure rates and restoration times for overhead lines, as functions of operating voltage, circuit length, and number of terminals; and to gain a better grasp of the nature and distribution of outage causes as a function of voltage.

2. To develop statistics on rare events such as three-phase faults at 500kV and 765kV.

3. To develop a better understanding of the nature and cause of related multiple outage events.

4. To correlate circuit availability with circuit design characteristics.

5. To determine how, in general, performance may have changed since the last survey in 1965.

6. To encourage and foster the uniform and consistent collection of transmission line outage data.

The 1985 survey differed from the 1949 and 1965 surveys in that it requested data on (a) related multiple outage events, (b) outage event start and end times, (c) 500kV and 765kV overhead lines, and (d) planned outage events. Outage rates are given on three bases: per 100-miles of circuit, per terminal, and per circuit.

Since the information summarized in this paper represents a second set of 1985 survey results, the numbering of tables and figures continues where [6] left off. That is, the first table of this paper is designated Table 18 and the first figure is Figure 2.

DATA REQUESTED

To use outage experience to estimate outage rates and repair times, two types of information are required: circuit exposure (population) data, and outage-event data. The desired exposure data (summarized in [6]) included basic data on each transmission circuit which could have contributed to the history of outage events. Required data on each circuit consisted of: circuit name (to which was appended the host utility identification number), operating voltage, length, number of terminals, and the specific time period over which the circuit, of a fixed design and configuration, was in service and subject to outage.

The request for outage data presumed that the responding utilities would translate data already collected into the format specified in the Transmission Outage Data Submission Guide (distributed with the request for data). In some cases this translation was performed on data that had already been assembled and pooled on a regional basis. In other cases, the data were assembled and submitted by individual utilities on coding forms.

Figure 2 illustrates the coding form used for the submission of outage event data. (An outage event may have involved a single circuit outage, or two or more related circuit outages.) This form provided a means for identifying the circuit(s) associated with the initiating cause (primary/independent or common-mode outage(s)), and for identifying any other circuit outage(s) required to isolate or remedy the problem (secondary/dependent outage(s)). Secondary outages were of two kinds: direct and indirect. If a secondary outage was a natural consequence of isolating the problem, it was considered a "direct" secondary. If the secondary outage was a result of a second failure, such as a stuck breaker or faulty protective relay, it was considered an "indirect" secondary.

Figure 3 shows the codes available to classify each circuit outage in an event according to: (a) the type of outage, (b) the relation of the particular circuit outage to the initiating cause, (c) whether the circuit was completely or only partially removed from service, (d) whether the initiating problem involved line equipment or terminal equipment, (e) the means by which the circuit was restored to service, (f) the type of fault, (g) the suspected cause of the outage, and (h) the effect of the outage event on the system or its components.

When the outage event involved more than one circuit in a common-mode fashion (because of common tower, common right-of-way, or common terminal), then a "common mode" designation was appropriate. If the initiating cause of an event had directly resulted in the common-mode outage of two or more circuits, then all of these circuits were considered primary outages. For example, if the fault had occurred on a bus, it may have been necessary to remove all circuits connected to that bus to isolate the fault. Each circuit would have been considered part of the same common-terminal, common-mode primary outage. Depending on network configuration, one or more secondary outages may also have been required to isolate the fault.

SURVEY RESPONSE

Seventy-eight utilities volunteered data, representing all nine USA regions of the North American Reliability Council (NERC). The Canadian utilities

X-273 REV. 6-85

TRANSMISSION CIRCUIT OUTAGE REPORTING FORM

PREPARER	DATE	PAGE OF

TRANSMISSION CIRCUIT OUTAGE DATA

TYP	UTILITY I.D.	EVENT NO	SEQ. NO	TRANSMISSION CIRCUIT IDENTIFICATION	SECT I.D.	START OF OUTAGE MO. DAY YR. HR MIN	END OF OUTAGE MO DAY YR HR MIN	OUTAGE CLASS	REST	FAULT TYPE	OUTAGE CAUSE	EFF
1	2	6	11	15		32	43	54		62	65	70

Figure 2. Transmission Circuit Outage Reporting Form.

Outage Classification (OUTAGE CLASS)

OUTAGE TYPE [Col 54]

- A - AUTOMATIC
- F - FORCED MANUAL
- S - PLANNED

MULTIPLE OUTAGES [Col 55-56]

- 1b̸ - PRIMARY
- DD - DIRECT SECONDARY
- DI - INDIRECT SECONDARY
- CB - COMMMON TERMINAL
- CR - COMMON ROW
- CT - COMMON TOWER

DEGREE OF OUTAGE [Col 57]

- C - COMPLETE
- P - PARTIAL

PROBLEM TYPE [Col 58]

- L - LINE RELATED
- T - TERMINAL RELATED
- U - UNKNOWN

Nature of Restoration (REST) [Col 60]

- A - AUTOMATIC
- M - MANUAL/SUPERVISORY
- R - REPAIR/REPLACE
- U - UNKNOWN

Fault Type [Col 62-63]

- b̸b̸ - NO FAULT OR NO OPEN PHASE
- 1G - SINGLE PHASE TO GRD
- 2P - PHASE TO PHASE
- 2G - DOUBLE PHASE TO GRD.
- 3P - THREE PHASE
- 3G - THREE PHASE TO GRD
- OP - OPEN PHASE
- UF - UNKNOWN

Suspected Cause of Outage (OUTAGE CAUSE) [Col 65-68]

DEFECTIVE POWER EQUIPMENT

- 1Lb̸b̸ - TRANSMISSION CIRCUIT EQUIP
- 1LCb̸ - CONDUCTOR
- 1LTb̸ - TOWER/STRUCTURE
- 1LSb̸ - SHIELD WIRE
- 1LIb̸ - INSULATOR/ INSULATION SYS.
- 1LXb̸ - CABLE
- 1Sb̸b̸ - TERMINAL/STATION EQUIP.
- 1SAb̸ - SURGE ARRESTOR
- 1SBb̸ - CIRCUIT BREAKER
- 1SCb̸ - SHUNT CAPACITOR BANK
- 1SPb̸ - PROTECTIVE SYSTEM
- 1STb̸ - BUS
- 1SSb̸ - DISCONNECT SWITCH
- 1TBb̸ - TRANSFORMER
- 1TRb̸ - SHUNT REACTOR BANK
- 1Ub̸b̸ - UNKNOWN

HUMAN ELEMENT

- 2b̸b̸b̸ - HUMAN ELEMENT RELATED
- 2Ab̸b̸ - IMPROPER RELAY SETTING
- 2Bb̸b̸ - INCORRECT INSTALLATION
- 2Cb̸b̸ - IMPROPER DESIGN/ APPLICATION
- 2Db̸b̸ - MAINTENANCE ACTIVITY
- 2Eb̸b̸ - CONSTRUCTION ACTIVITY
- 2Fb̸b̸ - VANDALISM OR SABOTAGE
- 2Gb̸b̸ - IMPROPER OPERATION

FOREIGN INTERFERENCE

- 3b̸b̸b̸ - FOREIGN INTERFERENCE
- 3Ab̸b̸ - ANIMAL
- 3Bb̸b̸ - BIRD
- 3Cb̸b̸ - CRANE
- 3Hb̸b̸ - HUMAN
- 3Kb̸b̸ - KITE OR OTHER OBJECT
- 3Pb̸b̸ - AIRCRAFT
- 3Tb̸b̸ - TREE
- 3Vb̸b̸ - VEHICLE
- 3Zb̸b̸ - ANOTHER LINE

POWER SYSTEM CONDITION/ CONFIGURATION

- 4b̸b̸b̸ - POWER SYS. COND./CONF
- 4Ab̸b̸ - STABLE OVERLOAD OPERATION
- 4Bb̸b̸ - STABLE OSCILLATION
- 4Cb̸b̸ - OUT OF STEP
- 4Db̸b̸ - OVERVOLTAGE
- 4Eb̸b̸ - LOSS OF GENERATOR
- 4Fb̸b̸ - RELAY INCORRECT OPERATION
- 4Gb̸b̸ - OVERLOAD TRIP
- 4Hb̸b̸ - UNDERVOLTAGE
- 4Ib̸b̸ - UNDERFREQUENCY
- 4Jb̸b̸ - SWITCHING SURGE (VOLTAGE)
- 4Kb̸b̸ - DYNAMIC OVERVOLTAGE
- 4Lb̸b̸ - INSTABILITY

OTHER

- 7Mb̸b̸ - MISCELLANEOUS OR OTHER
- 7Ub̸b̸ - UNKNOWN

ENVIRONMENTAL

- 5b̸b̸b̸ - ENVIRONMENT
- 5Ab̸b̸ - LIGHTNING
- 5Bb̸b̸ - WEATHER
- 5BRN - RAIN
- 5BSN - SNOW
- 5BSL - SLEET
- 5BIb̸ - ICE
- 5BHL - HAIL
- 5BWH - HIGH WIND
- 5BHC - HURRICANE
- 5BTH - THUNDERSTORM
- 5BTN - TORNADO
- 5Cb̸b̸ - CONTAMINATION
- 5CSM - SMOG
- 5CSb̸ - SALT
- 5CBD - BIRD DROPPINGS
- 5CIb̸ - INDUSTRIAL
- 5CAG - AGRICULTURE
- 5EMb̸ - EARTH MOVEMENT
- 5FRb̸ - FIRE
- 5FLb̸ - FLOOD
- 5Gb̸b̸ - GALLOPING CONDUCTORS
- 5Hb̸b̸ - AEOLIAN VIBRATION

SCHEDULED OUTAGE

- 6b̸b̸b̸ - UNSPECIFIED PLANNED OUTAGE
- 6Ab̸b̸ - CONSTR., INSTALL., MODIFICATION
- 6Bb̸b̸ - TRANSMISSION CIRCUIT MAINT.
- 6Cb̸b̸ - TERMINAL EQUIP. MAINT.
- 6Db̸b̸ - TEST OR INSPECTION
- 6Eb̸b̸ - FOREIGN UTILITY REQUEST
- 6Fb̸b̸ - SYSTEM CONDITION
- 6Gb̸b̸ - ROUTINE OPERATION

Effects of Outage (EFF) [Col 70]

- A - CASCADING
- B - LOSS OF GEN
- C - LOSS OF TERM BANK
- D - LOSS OF LOAD
- E - INSTABILITY
- F - LOSS OF INTERCONNECTION
- G - OVERLOAD
- H - LINE DAMAGE
- I - EQUIPMENT DAMAGE
- J - CONTROLLED LOAD SHED.
- K - BLACKOUT
- L - LOSS OF OTHER CIRCUITS (< 230kv)
- M - NO ADVERSE EFFECT

Note: Under "Suspected Cause of Outage," the symbol "b̸" represents a blank space.

Figure 3. Transmission Circuit Outage Reporting Codes.

were represented in an additional single submission by the Canadian Electrical Association. A total of 38 489 outage records were judged valid and accepted. These consisted of outage types: automatic, forced-manual, and planned, and included primary, secondary, and common-mode outage classes. These outages were derived from 14 120 circuit-years or 583 712 mile-years of circuit exposure. The data submitted were derived from circuits of voltage 230kV and higher in service during various periods within the 1965-1985 time frame. Table 1 (repeated from [6]) provides a snapshot on July 1 of each year of the circuit population contributing to the database. In those NERC regions where the submission was based on regionally pooled data, the number of circuits shown in Table 1 remains roughly constant from year to year over the period that data were submitted. In those regions where submissions were by individual utilities, the number of participating circuits displays a wider year-to-year variation.

Circuit outage event data were submitted with varying levels of care and detail. Some utilities reported single and multiple-line outages as well as forced and scheduled outages, providing start and end times to the minute, carefully conforming to the recommended format, and using the codes defined in the Transmission Outage Data Submission Manual. Other utilities were less careful, and perhaps reported all circuit outages as independent events without identifying related outages. Some gave outage start and end dates, but omitted the time of day (hour and minute). In some cases, important data fields were left blank. The instructions for coding outages were at times misinterpreted.

Some utilities simply submitted their data in their own specific format, leaving the Working Group with the option to convert the data to the desired format. In the latter case, difficulties were often encountered due to a lack of information to guide the required conversion.

Only those outages records which satisfied the minimum data requirements were included in the database. An acceptable outage record was one that provided the minimum required data on an outage event, and documented an event which occurred within the in-service period established by a corresponding valid circuit exposure record.

RESULTS

In the letter requesting circuit outage event data, utilities were assured that all data that were submitted would be pooled and the results presented in summary form only. In an effort to publish survey results without further delay, only basic data analysis has been performed. More detailed analysis, such as the correlation of circuit design characteristics and circuit availability, may yet be performed, depending on the level of interest revealed in the discussion of this paper.

Data Summaries

Table 18 summarizes the nature of the primary forced outages. A primary outage is the circuit that experiences the initiating event. Although two or more circuits involved in a common-mode outage event may also experience an initiating event, the decision was made to exclude these multiple related outage events in Table 18. As the title of Table 18 implies, secondary circuit outages are also not included. Table 18 classifies 15 525 primary forced outages by cause, voltage, problem type (line-related, terminal-related or unknown), and general duration ("momentary" for restoration times less than or equal to one minute, and "sustained" for restoration times equal to or greater than two minutes). The causes of the primary outages are classified into the same categories used in the Outage Reporting Form (see Figure 3). If the problem type was not specified, and it could not be deduced from information on the outage cause (refer to section entitled Data Enhancement), it was classified as "Unknown."

Outage rates are expressed per 100-mile-year for line-related outages, per terminal-year for terminal-related outages, and per circuit-year for all outages combined (terminal-related, line-related, and unknown). In calculating terminal-years exposure, if the number of terminals of any circuit was not specified, it was assumed to have two.

The exposure to outage is summarized at the bottom of Table 18. This represents the mile-years (in hundreds), terminal-years, or circuit-years that were exposed to failure. The total number of line-related primary outages for each voltage is normalized by line

Table 1. Reported Line Population (Number of Circuits) *.

	BY REGION										BY VOLTAGE LEVEL			
	CEA	NPCC	MAPP	SPP	SERC	MAAC	MAIN	ECAR	ERCOT	WSCC	230	345	500	765
1965	0	0	0	6	12	0	0	0	0	0	18	0	0	0
1966	0	0	0	6	14	0	0	0	0	1	21	0	0	0
1967	0	0	0	6	17	0	0	0	0	1	24	0	0	0
1968	0	0	0	10	21	0	0	0	0	1	28	4	0	0
1969	0	0	0	10	22	0	0	0	0	2	29	5	0	0
1970	0	0	0	11	26	0	0	0	0	2	34	5	0	0
1971	0	0	1	19	28	0	0	0	0	2	43	7	0	0
1972	0	0	1	25	34	0	0	0	0	21	55	7	19	0
1973	0	0	1	30	38	0	0	0	0	21	62	9	19	0
1974	0	0	1	37	41	0	0	0	1	28	69	14	25	0
1975	0	0	2	38	46	0	94	103	3	28	91	197	25	1
1976	0	22	2	42	54	0	104	238	11	28	108	334	44	15
1977	0	22	111	49	58	0	113	254	15	29	163	422	45	21
1978	0	22	120	55	64	0	115	263	19	32	178	446	45	21
1979	0	24	134	64	99	376	124	269	20	30	566	479	74	21
1980	502	24	149	66	215	381	123	283	28	31	1021	595	125	61
1981	511	49	161	69	217	389	125	290	38	33	1045	640	130	67
1982	526	49	174	71	218	393	132	302	42	34	1062	664	143	72
1983	550	23	177	75	262	393	123	315	46	36	1071	660	184	85
1984	532	23	0	77	266	397	93	323	49	36	932	567	204	93
1985	0	23	0	63	268	402	0	0	46	37	603	104	130	2

* As of July 1 for the years shown. (Table 1 is repeated from [6].)

Table 18. Primary Automatic and Forced Manual Outages (1) by Cause, Voltage, Problem Type, and Duration Class (2), and Estimated Forced Outage Rates.

CAUSE	230 KV						345 KV						500 KV						765 KV					
	LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN	
	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.
DEFECTIVE POWER EQUIPMENT																								
TRANSMISSION CIRCUIT EQUIP	6	55	0	1	0	0	12	70	0	0	0	0	6	6	0	0	0	0	0	4	0	0	0	0
CONDUCTOR	2	59	0	1	0	1	0	6	0	0	0	0	0	4	0	0	0	0	0	8	0	0	0	0
TOWER/STRUCTURE	2	37	0	1	0	3	2	11	0	0	0	0	0	3	0	0	0	0	0	5	0	0	0	0
SHIELD WIRE	7	100	0	0	0	0	7	21	0	1	0	0	1	1	0	0	0	0	4	15	0	0	0	0
INSULATOR/INSULATION SYSTEM	9	45	2	6	0	1	16	37	2	0	0	1	3	12	0	0	0	0	0	13	0	0	0	0
CABLE	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TERMINAL/STATION EQUIPMENT	6	15	6	47	0	0	2	2	156	543	0	0	0	2	4	44	0	0	0	0	29	91	0	0
SURGE ARRESTOR	2	3	1	7	0	0	0	3	1	5	0	0	0	1	0	1	0	0	0	0	0	0	0	0
CIRCUIT BREAKER	0	3	7	59	0	0	2	4	1	11	0	1	0	0	0	28	0	0	0	0	0	0	0	0
SHUNT CAPACITOR BANK	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
PROTECTIVE SYSTEM	2	4	32	185	0	0	0	0	96	194	1	1	2	15	14	28	0	0	0	0	2	4	0	0
BUS	0	0	0	4	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
DISCONNECT SWITCH	0	0	1	10	0	0	0	0	0	4	0	0	1	1	0	5	0	0	0	0	0	0	0	0
TRANSFORMER	2	2	22	36	0	0	0	1	2	6	0	0	1	0	1	3	0	0	0	0	0	1	0	0
SHUNT REACTOR BANK	0	0	0	1	0	0	0	1	0	2	0	0	0	0	0	1	0	0	0	0	0	2	0	0
UNKNOWN	10	16	0	0	2	5	9	42	4	5	18	11	0	1	2	2	0	0	0	0	0	0	0	0
SUB-TOTAL (DEFECTIVE POWER EQUIPMENT)	50	339	73	359	2	10	50	200	262	772	19	14	15	47	22	113	0	0	4	45	31	98	0	0
HUMAN ELEMENT																								
HUMAN ELEMENT RELATED	75	164	31	56	0	0	0	46	118	228	0	0	16	24	4	14	0	0	5	43	14	17	0	0
IMPROPER RELAY SETTING	0	0	3	14	0	0	0	1	1	1	0	0	0	0	1	2	0	0	0	0	0	0	0	0
INCORRECT INSTALLATION	0	1	0	4	0	0	0	0	1	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IMPROPER DESIGN/APPLICATION	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
MAINTENANCE ACTIVITY	1	14	1	3	0	1	3	5	12	18	0	2	0	0	2	7	0	0	0	0	0	0	0	0
CONSTRUCTION ACTIVITY	0	10	2	2	0	0	1	1	1	0	0	0	0	2	0	9	0	0	0	0	0	0	0	0
VANDALISM OR SABOTAGE	2	19	1	1	0	0	0	14	0	1	0	0	1	1	0	0	0	0	0	2	0	0	0	0
IMPROPER OPERATION	0	1	20	30	0	0	3	5	125	124	0	0	3	12	5	13	0	0	0	0	5	5	0	0
SUB-TOTAL (HUMAN ERROR)	78	229	58	112	0	1	7	72	258	377	0	2	20	41	12	45	0	0	5	45	19	22	0	0
FOREIGN INTERFERENCE																								
FOREIGN INTERFERENCE	16	99	0	0	0	0	0	6	0	0	0	0	0	7	0	1	0	0	0	3	0	0	0	0
ANIMAL	0	0	3	1	0	0	3	0	1	1	0	0	0	0	1	0	0	0	4	0	0	0	0	0
BIRD	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
CRANE	2	4	0	0	0	0	4	15	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0
HUMAN	0	0	2	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
KITE OR OTHER OBJECT	3	6	0	1	0	0	1	1	0	0	0	0	1	5	0	0	0	0	0	0	0	0	0	0
AIRCRAFT	1	19	0	1	0	1	4	8	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0
TREE	18	447	1	1	0	1	50	87	1	0	1	2	23	29	0	1	0	0	0	2	0	0	0	0
VEHICLE	3	31	0	0	0	0	3	3	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0
ANOTHER LINE	0	1	1	5	0	0	0	24	0	2	2	1	0	0	1	0	0	0	0	0	0	0	0	0
SUB-TOTAL (FOREIGN INTERFERENCE)	44	608	7	9	0	2	65	145	2	4	3	3	26	60	2	3	0	0	4	5	0	0	0	0
POWER SYSTEM CONDITION/CONFIGURATION																								
POWER SYSTEM. CONDITION/CONF.	9	21	82	82	0	3	0	37	0	59	0	1	7	7	0	2	0	8	1	3	0	0	0	0
STABLE OVERLOAD OPERATION	0	0	0	2	0	0	0	1	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
STABLE OSCILLATION	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OUT OF STEP	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OVERVOLTAGE	0	1	0	20	0	0	0	7	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOSS OF GENERATOR	0	0	0	1	0	0	0	0	0	4	0	1	0	0	0	1	0	0	0	0	0	0	0	0
RELAY INCORRECT OPERATION	2	3	3	0	0	0	1	7	2	9	0	0	1	1	0	12	0	0	0	0	0	4	0	0
OVERLOAD TRIP	0	0	1	40	0	0	0	1	0	15	1	0	0	5	0	7	0	0	0	0	0	3	0	0
UNDERVOLTAGE	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UNDERFREQUENCY	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SWITCHING SURGE (VOLTAGE)	0	0	2	4	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
DYNAMIC OVERVOLTAGE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INSTABILITY	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
SUB-TOTAL (POWER SYSTEM COND./CONF.)	11	33	88	135	0	3	1	53	4	101	2	2	6	13	1	22	0	8	1	4	0	7	0	0

(Continued)

Table 18. (Continued)

CAUSE	230 KV						345 KV						500 KV						765 KV					
	LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN	
	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.
ENVIRONMENT																								
ENVIRONMENT	221	311	5	14	0	0	126	273	12	8	0	0	2	3	1	0	0	0	0	8	0	0	0	0
LIGHTNING	843	444	4	8	5	1	1 335	268	0	2	11	13	261	90	1	0	0	0	132	51	0	0	0	0
WEATHER	181	226	0	0	0	8	28	82	0	0	72	18	192	18	0	0	0	0	13	21	0	0	0	0
HURRICANE	6	10	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HAIL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ICE	5	10	0	6	0	5	108	89	0	0	0	8	0	4	0	0	0	0	8	8	0	0	0	0
RAIN	3	3	0	3	0	2	2	0	0	0	0	0	2	5	0	0	0	0	0	0	0	0	0	0
SLEET	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNOW	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
THUNDERSTORM	35	32	0	0	1	11	9	32	2	0	3	3	0	1	0	1	0	2	0	0	0	0	0	0
TORNADO	1	6	0	0	0	2	1	11	0	0	0	3	0	2	0	0	0	0	0	0	0	0	0	0
HIGH WIND	15	35	3	0	0	1	34	75	0	0	1	1	1	9	0	0	0	0	18	5	0	0	0	0
CONTAMINATION	0	71	0	0	0	0	40	21	2	12	4	3	25	6	0	0	0	0	0	2	0	0	0	0
AGRICULTURE	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
BIRD DROPPINGS	0	0	0	0	0	0	0	3	0	0	0	0	15	8	0	0	0	0	0	0	0	0	0	0
INDUSTRIAL	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SALT	0	0	0	0	0	0	0	4	3	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SMOG	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EARTH MOVEMENT	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FLOOD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FIRE	7	6	0	4	0	1	7	13	0	1	0	0	26	30	1	1	0	0	0	0	0	0	0	0
GALLOPING CONDUCTORS	0	0	0	0	0	0	24	51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AEOLIAN VIBRATION	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SUB-TOTAL (ENVIRONMENT)	1 321	1 159	13	35	5	31	1 723	905	19	27	91	49	545	174	3	2	0	2	171	95	0	0	0	0
OTHER																								
MISCELLANEOUS OR OTHER	4	265	2	0	0	4	112	301	32	127	227	258	5	19	0	0	9	13	0	3	1	0	29	31
UNKNOWN	147	318	24	13	58	127	65	83	2	6	620	471	50	47	4	2	15	13	3	17	0	4	33	14
SUB-TOTAL (OTHER)	151	583	26	13	58	131	177	384	34	133	647	729	55	66	4	2	24	26	3	20	1	4	62	45
SUB-TOTAL (NON-SCHEDULED OUTAGES)	1 655	2 951	265	663	66	178	2 023	1 739	579	1 414	962	799	669	401	44	187	24	34	188	214	51	131	62	45
SCHEDULED OUTAGE (3)																								
UNSPECIFIED PLANNED	1	0	2	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
CONSTR., INSTALL, MODIFICATION	3	0	0	1	0	0	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TRANSMISSION CIRCUIT	1	29	0	3	0	0	0	7	0	2	0	0	0	8	0	1	0	0	0	0	0	0	0	0
TERMINAL EQUIP MAINTENANCE	0	0	4	19	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TEST OR INSPECTION	0	1	6	10	0	1	1	0	0	6	0	0	0	0	0	5	0	0	0	0	0	0	0	0
FOREIGN UTILITY REQUEST	0	1	0	3	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SYSTEM CONDITION	0	7	6	15	0	0	0	0	0	6	0	0	0	0	0	8	0	0	0	0	0	0	0	0
ROUTINE OPERATION	0	3	0	4	0	0	0	2	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
SUB-TOTAL (SCHEDULED OUTAGES)	5	41	18	56	0	3	1	13	0	16	0	0	0	12	0	16	0	0	0	0	0	0	0	0
TOTAL NUMBER OF OUTAGES	1 660	2 992	283	719	66	181	2 024	1 752	579	1 430	962	799	669	413	44	203	24	34	188	214	51	131	62	45
EXPOSURE																								
MILE-YEARS (HUNDREDS)	2 325		----		----		2 329		----		----		784		----		----		399		----		----	
TERMINAL-YEARS	----		11 681 (4)		----		----		9 490 (4)		----		----		2 089 (4)		----		----		433 (4)		----	
CIRCUIT-YEARS	7 265		5 497 (4)		5 497 (4)		5 177		4 726 (4)		4 726 (4)		1 221		1 037 (4)		1 037 (4)		456		216 (4)		216 (4)	
OUTAGE RATE																								
PER 100 MILE-YEAR	0.714	1.287	----	----	----	----	0.869	0.752	----	----	----	----	0.853	0.527	----	----	----	----	0.471	0.536	----	----	----	----
PER TERMINAL-YEAR	----	----	0.024	0.062	----	----	----	----	0.061	0.151	----	----	----	----	0.021	0.097	----	----	----	----	0.118	0.302	----	----
PER CIRCUIT-YEAR	0.226	0.412	0.051	0.131	0.012	0.033	0.391	0.338	0.123	0.303	0.204	0.169	0.548	0.388	0.042	0.196	0.023	0.033	0.412	0.469	0.236	0.606	0.287	0.208

NOTES:

1. EXCLUDES COMMON MODE OUTAGES.
2. EXCLUDES ALL OUTAGES REPORTED WITH INCOMPLETE DURATION DATA.
3. REPORTED AS 'AUTOMATIC' OR 'FORCED MANUAL' OUTAGES.
4. EXCLUDES CIRCUITS WHOSE OUTAGES WERE REPORTED WITH INCOMPLETE DURATION DATA.

exposure (in 100-mile-years) to obtain a line outage rate per 100-miles per year. In a similar fashion, the total number of terminal-related primary outages is normalized by the terminal exposure (in terminal-years) to estimate a line outage rate per terminal per year. The total number of outages for each voltage level (line-related, terminal-related, and unknown) is normalized by the number of circuit-years to develop a general outage rate per circuit per year.

As an example of the use of the outage rates given at the bottom of Table 18, consider the calculation of the rate of occurrence of sustained outages on a particular 230kV circuit, ORS(230), as a function of circuit length and number of circuit terminals. The following equation would be used.

$$ORS(230) = ORSL(230) * \frac{\text{Circuit Length in Miles}}{100} + ORST(230) * (\text{No. of Circuit Terminals}) + ORSU(230)$$

where ORS(230) is the rate of occurrence (per year) of sustained outages for a particular 230kV circuit,
ORSL(230) is the sustained outage rate per 100 miles for 230kV circuits,
ORST(230) is the sustained outage rate per terminal for 230kV circuits, and
ORSU(230) is the sustained outage rate for the average 230kV circuit reflecting those cases where the origin of the problem is either unknown or not specified.

Thus, for a three-terminal, 50-mile, 230kV circuit,

$$ORS = 1.287 * \frac{50}{100} + 0.062 * 3 + 0.033$$
$$= 0.8625 \text{ sustained forced outages per year.}$$

To calculate the rate of occurrence of sustained outages of the average 230kV circuit, ORSA(230), the following equation would be used.

$$ORSA(230) = ORSLA(230) + ORSTA(230) + ORSU(230)$$

where ORSA(230) is the sustained outage rate (per year) for the average 230kV circuit,
ORSLA(230) is the sustained outage rate for the average 230kV circuit due specifically to line-related outages,
ORSTA(230) is the sustained outage rate for the average 230kV circuit due specifically to terminal-related outages,
ORSU(230) is defined above.

Thus, for the average 230kV line,

$$ORSA(230) = 0.412 + 0.131 + 0.033$$
$$= 0.576 \text{ sustained forced outages per year.}$$

The reader is cautioned not to draw conclusions about the ratio of line-related to terminal-related outages reported in Table 18, since a significant number of terminal-related outage records were removed from the database due to an irreconcilable data deficiency.

Table 19 summarizes the distribution of causes, by voltage, of the circuit outages designated as "Planned." Of the 78 responding utilities, 63 reported planned outages. After reviewing the ratio of reported planned outages to the total number of reported outages for each utility, it was observed that some utilities seemed to report planned outages only on an occasional basis. To adjust for this inconsistency in the calculation of planned outage rates, only the planned outages and circuit exposures of those utilities whose ratio of reported planned outages to total reported outages exceeded 15% were used. As a result, Table 19 represents the planned outages and circuit-years exposure of 58 utilities. The number of planned outage records used drops by a mere 0.03% (from 21,321 to 21,259). The ratios for the remaining 58 utilities ranged from 25% to 98% (with an average of 65%).

Table 19 includes 129 of the 181 "Automatic" or "Forced Manual" outages with "Scheduled" outage cause, listed in Table 18. These belong to the 58 utilities assumed to have reported all planned outages.

Table 20 classifies the various combinations of one or more circuit outages that comprise the database of outage events. Since the data from several NERC regions consisted only of single-circuit outage events, circuit outages with identical initiation times (to the minute) within the same utility were identified. There is a high probability that these simultaneous circuit outages were, indeed, related events. These are summarized in Table 20 as "Independent Simultaneous" outages. (Note that the independent simultaneous multiple-outage events may easily be recast as independent events. For example, an independent simultaneous event involving three circuit outages in Table 20 may alternatively be considered as three independent events, each involving one circuit.)

Excluded from Table 20 are the data from those submissions consisting entirely of independent primary outages where the duration of the outage was given, rather than the specific outage start and end times (a result of a required data conversion). In this case, it was impossible to identify simultaneous start times.

When an outage event involved a number of circuits, each with a different "Multiple Outage" code, the question arises: What multiple-outage classification should be assigned to this outage? The Working Group's response was arbitrary, but rational. The seven different multiple-outage types were subjectively ranked in order of decreasing probability of occurrence:

- Independent
- Independent Simultaneous
- Direct Secondary
- Common-Terminal Common Mode
- Indirect Secondary
- Common-Tower Common Mode
- Common-Right-of-Way Common Mode

In Table 20, an event is classified according to the least probable multiple-outage type recorded for one or more circuits within the event, and by the voltage of the circuit(s) on which this least probable outage type occurred. For example, using the above ordering for decreasing probability, if an event had involved three circuit outages of types: primary, direct secondary, and indirect secondary, the three-circuit event would have been classified "indirect secondary"--the least probable outage type in the event. The event would have been classified under the voltage level of the circuit whose outage was a specific consequence of the indirect secondary occurrence. As another example, consider an event that had included a common-tower common-mode outage of two lines and, because of a stuck breaker, also had included an indirect secondary outage. This

CAUSE	230KV	345KV	500KV	765KV
UNSPECIFIED PLANNED	29.68%	57.19%	40.87%	84.69%
CONSTRUCTION, INSTALLATION, MODIFICATION	11.51%	10.55%	4.89%	1.26%
TRANSMISSION CIRCUIT MAINTENANCE	18.86%	11.22%	8.66%	1.83%
TERMINAL EQUIPMENT MAINTENANCE	13.28%	12.12%	8.40%	3.67%
TEST OR INSPECTION	11.45%	6.32%	11.84%	1.61%
FOREIGN UTILITY REQUEST	1.83%	0.36%	1.19%	0.00%
SYSTEM CONDITION	0.52%	1.83%	21.36%	6.94%
ROUTINE OPERATION	8.55%	0.22%	1.79%	0.00%
OTHER THAN SCHEDULED (2)	4.33%	0.20%	0.99%	0.00%
TOTAL PERCENT	100%	100%	100%	100%
TOTAL NUMBER OF OUTAGES (3) (4)	5 031	12 972	1 512	1 744
SCHEDULED OUTAGES FROM TABLE 18 (5)	78	28	23	0
TOTAL SCHEDULED OUTAGES	5 109	13 000	1 535	1 744
TOTAL NUMBER OF CIRCUIT-YEARS (3)	2 415	4 112	411	207
PLANNED OUTAGE RATE (PER CIRCUIT-YEAR)	2.12	3.16	3.73	8.41

Notes: (1) Excludes outages classified as secondary or common mode.
(2) Outage Type listed as "Planned" but Outage Cause was other than "Scheduled."
(3) Includes circuits from only those utilities whose reported "Planned" outages comprise at least 15% of their total reported outages.
(4) Total excludes the 181 outages in Table 18 with "Scheduled" Outage Cause.
(5) 129 "Scheduled" outages from Table 18 from those utilities whose reported "Planned" outages comprise at least 15% of their total reported outages.

Table 20. Classification of Multiple Outage Events by Outage Type and Voltage.

VOLTAGE (KV)	TOTAL CIRCUITS INVOLVED IN OUTAGE EVENT	INDEPENDENT SINGLE AND SIMULTANEOUS	INVOLVING DIRECT SECONDARY OUTAGES	INVOLVING COMMON-TERMINAL COMMON-MODE OUTAGES	INVOLVING INDIRECT SECONDARY OUTAGES	INVOLVING COMMON-TOWER COMMON-MODE OUTAGES	INVOLVING COMMON-R.O.W. COMMON-MODE OUTAGES
230	1	3 320	41	11	6	2	0
	2	303	46	26	26	1	0
	3	39	4	2	6	0	0
	4	18	0	1	3	1	0
	5	7	1	0	0	1	0
	6	0	0	0	0	0	0
	7	3	0	0	0	0	0
	8	2	0	0	0	0	0
	Total 230KV	3 692	92	40	41	5	0
345	1	5 807	20	9	9	3	4
	2	577	52	61	14	18	4
	3	99	8	13	2	5	1
	4	16	0	2	0	1	0
	5	1	1	0	0	0	0
	6	1	0	2	1	0	0
	7	1	0	0	0	0	0
	Total 345KV	6 502	81	87	26	27	9
500	1	721	10	5	1	0	0
	2	35	58	4	4	0	0
	3	3	19	0	1	0	0
	4	0	2	0	0	0	0
	5	0	1	0	0	0	0
	Total 500KV	759	90	9	6	0	0
765	1	295	1	0	0	0	0
	2	36	12	4	0	0	0
	3	2	4	1	1	0	0
	4	2	0	0	0	0	0
	5	0	0	0	0	0	0
	6	1	0	0	0	0	0
	Total 765KV	336	17	5	1	0	0
Grand Total		11 289	280	141	74	32	9

event would have been classified "common-tower common mode." The voltage level under which the event would have been classified was that of the common tower line. The above ordering of multiple outage types is somewhat validated by the decreasing magnitude of the Grand Totals in Table 20, as one moves from left to right, corresponding to moving from top to bottom of the above list of multiple outage types.

The first row of entries in Table 20 lists multiple-line outages that appear to involve only a single circuit. These entries arise where the multiple outage involved one or more circuits operating at a voltage lower than 230kV or when the initiating event was a planned outage. Neither lower voltage nor planned circuit outages would appear in the forced outage database on which Table 20 is based.

Table 21 summarizes the incidence of each of the various types of fault that initiated primary outages. These are classified by voltage, by problem type (line-related, terminal-related, or unknown), and whether the resulting outage was momentary or sustained. A high percentage of the fault types were designated as "Unknown" or were not classified at all. Table 21 includes the 181 automatic and forced-manual outage events with "Scheduled" outage causes presented in Table 18.

Table 22 summarizes the distribution of the restoration times of automatic and forced-manual outage events. The first portion of the table reports an analysis of the outage durations that excludes all forced outages of unusually long duration (arbitrarily defined here as outages lasting more than 1000 hours). Inclusion of even one such outage event would significantly increase average duration. The rationale for this action was that, even though such an outage may have, in fact, begun as a forced outage, it was eventually transformed to "scheduled" outage as the power system was adjusted to reestablish a secure and economic operating state. The extracted outages are summarized in the second portion of Table 22.

If the outage duration were exponentially distributed, the ratio of the average to the median would be .632/.500 or 1.264. In Table 22 the ratio ranges between 9.1 and 64.1. It is reasonable to conclude that the urgency of repair (e.g., working overtime, not working overtime, etc.) varies from outage to outage as do the requirements for restoration (switching, repair, replacement, etc.).

Table 23 summarizes by voltage level, first, the incidence of the different outage types. Of a total of 36 846 primary outage records, 15 525 were "Automatic" or "Forced-Manual" outages, the remaining 21 321 were "Planned." At 345kV and above, there is a high ratio of "Forced-Manual, Sustained" outages to "Automatic, Sustained" outages relative to the same ratio at 230kV. This raises a question about postponable outages and the variations among utilities in the distinction between a deferred forced-manual outage and a scheduled outage. (Reference [5] provides a definition for Scheduled Outage: "An intentional manual outage that could have been deferred without increasing risk to human life, risk to property, or damage to equipment.") Unfortunately, information on this arbitrary distinction was not requested in the survey.

The second portion of Table 23 summarizes the degrees of sustained primary forced outage. Since most circuits have only two terminals and no sectionalizing breakers, a fault on the circuit usually resulted in completely de-energizing the circuit. A terminal fault may or may not have de-energized the circuit.

The third portion of Table 23 shows the variation in the effect of sustained primary forced outages. Nearly 30% of all sustained outages had no adverse effect; the effect of 62% were not classified.

Table 24 summarizes the data reported on the nature of restoration following forced (automatic, forced-manual, and not-specified) and planned primary outages. As expected, most planned outages are sustained in nature and are returned to service through manual or supervisory-controlled switching. Most sustained forced outages are similarly restored. Most momentary forced outages are returned through automatic switching. In this table, planned outage events with missing end times were assumed to be momentary.

DATA ENHANCEMENT

Often outage records were found to be incomplete. Depending on which fields happened to have been left blank, the use of an outage record may range from limited application to none at all. Certain inferences, however, were made based on information provided elsewhere in the same outage record (that is, the start and end times of the outage, and outage cause). This information provided a basis for filling certain blank fields with codes other than an "NC" for "Not Classified." The bases for assigning a meaningful code to particular fields are as follows. (Any addition to a data record was identified in a new field of what became an augmented data record; the original record was not altered.)

Outage Type An outage may be classified as automatic, forced-manual, or planned based on how it was initiated. When the Outage Type field was left blank, the outage was classified as "Automatic" if the outage cause was one that would precipitate a phase-to-ground fault. Referring to the Cause Codes given in Figure 3, this was considered the case for outage causes: Contamination (5C), and Foreign Interference (cause codes with prefix "3") except for Human (3H) and Tree (3T). An outage was also classified "Automatic" if the outage cause was identified as a Defective Protective System (1SP), Improper Relay Setting (2A), or Power System Condition: Out of Step (4C), Relay Incorrect Operation (4F), Overload Trip (4G), Switching Surge (4J), Dynamic Overvoltage (4K), or Instability (4L). If the outage type was left blank and the outage cause was any scheduled outage (cause code with prefix "6"), the outage type was classified "Planned."

Multiple Outages In cases where a utility had left the Multiple Outage field blank, the circuit outage was assumed to be "Primary/Independent" (I). If, however, it had the same start-time (to the minute) as one or more other circuit outages reported by the same utility, it was, in addition, recognized as "Simultaneous" (IS). If a utility was observed to report all circuit outages as primary/independent, and it was also observed that some of that utility's circuit outages had identical start-times, an "S" was added to the existing "I" to yield the independent and simultaneous code (IS). In either case, the "IS" indicates that the circuit outages in the same utility with simultaneous start times may have been related and part of a single event.

Fault Type The Transmission Outage Data Submission Guide stated that a blank entry in the "Fault Type" data field is intended to mean "No Fault." This, however, led to some confusion in the interpretation of the data submitted. That is, when the data submitter made no attempt to enter fault-type information, care was required not to confuse this with a series of outages each of which had "No Fault." An "NC" was

Table 21. Primary Automatic and Forced Manual Outages * by Fault Type, Problem Type, and Duration Class.

FAULT TYPE	230 KV						345 KV					
	LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN	
	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM	SUST.	MOM.	SUST.	MOM	SUST
NO FAULT OR NO OPEN	21.14%	18.01%	89.75%	74.97%	16.67%	12.71%	2.27%	11.02%	15.54%	27.48%	2.29%	3.25%
SINGLE PHASE TO GROUND	52.89%	24.57%	4.95%	6.54%	34.85%	11.60%	17.29%	38.41%	5.70%	3.36%	14.97%	11.39%
PHASE TO PHASE	5.36%	6.99%	0.35%	1.95%	3.03%	0.55%	0.64%	2.23%	0.17%	0.56%	0.83%	0.13%
DOUBLE PHASE TO GROUND	3.61%	2.51%	0.00%	0.83%	0.00%	2.21%	0.20%	0.74%	0.17%	0.35%	0.21%	0.38%
THREE PHASE	1.14%	1.27%	0.00%	0.00%	0.00%	0.00%	0.30%	0.17%	0.00%	0.14%	0.00%	0.00%
THREE PHASE TO GROUND	0.00%	0.97%	0.00%	0.63%	0.00%	0.00%	0.15%	1.60%	0.17%	0.00%	0.00%	0.25%
OPEN PHASE	0.06%	0.30%	0.00%	0.14%	0.00%	0.00%	0.00%	0.06%	0.00%	0.00%	0.00%	0.00%
UNKNOWN	15.18%	45.09%	3.18%	13.91%	45.45%	72.38%	1.93%	5.02%	3.80%	3.15%	6.86%	18.02%
NOT CLASSIFIED	0.60%	0.30%	1.77%	0.83%	0.00%	0.55%	77.22%	40.75%	74.44%	64.97%	74.84%	66.58%
TOTAL PERCENT	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
TOTAL NO OF FAULTS	1 660	2 992	283	719	66	181	2 024	1 752	579	1 430	962	799

FAULT TYPE	500 KV						765 KV					
	LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN	
	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.
NO FAULT OR NO OPEN	5.23%	27.12%	68.18%	67.49%	0.00%	32.35%	1.60%	29.44%	0.00%	11.45%	0.00%	0.00%
SINGLE PHASE TO GROUND	74.59%	50.36%	4.55%	6.87%	0.00%	0.00%	39.36%	43.46%	0.00%	0.00%	0.00%	0.00%
PHASE TO PHASE	3.44%	5.08%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
DOUBLE PHASE TO GROUND	4.19%	5.33%	0.00%	0.49%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
THREE PHASE	0.60%	1.21%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
THREE PHASE TO GROUND	0.15%	1.21%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
OPEN PHASE	0.00%	1.21%	0.00%	0.49%	0.00%	0.00%	1.06%	3.27%	0.00%	0.00%	0.00%	0.00%
UNKNOWN	1.20%	1.69%	2.27%	2.46%	0.00%	11.76%	0.53%	1.87%	0.00%	0.76%	0.00%	2.22%
NOT CLASSIFIED	10.61%	6.78%	25.00%	20.20%	100.00%	55.88%	57.45%	21.96%	100.00%	87.79%	100.00%	97.78%
TOTAL PERCENT	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
TOTAL NO OF FAULTS	669	413	44	203	24	34	188	214	51	131	82	45

* NOTE: EXCLUDES COMMON MODE OUTAGES

Table 22. *Statistics of the Outage Durations (in Hours) of Sustained Primary Automatic and Forced Manual Outages (1, 2, 3) by Voltage and Problem Type.*

	230KV			345KV			500KV			765KV		
	LINE RELATED OUTAGES	TERMINAL RELATED OUTAGES	ALL (4) FORCED OUTAGES	LINE RELATED OUTAGES	TERMINAL RELATED OUTAGES	ALL (4) FORCED OUTAGES	LINE RELATED OUTAGES	TERMINAL RELATED OUTAGES	ALL (4) FORCED OUTAGES	LINE RELATED OUTAGES	TERMINAL RELATED OUTAGES	ALL (4) FORCED OUTAGES
AVERAGE	7.94	9.85	8.44	16.65	10.68	14.29	17.94	10.82	15.32	14.2	13.91	12.87
5 PERCENTILE	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.12	0.03
10 PERCENTILE	0.02	0.03	0.02	0.02	0.05	0.03	0.03	0.05	0.03	0.05	0.28	0.1
25 PERCENTILE	0.03	0.13	0.03	0.05	0.17	0.08	0.08	0.17	0.1	0.2	0.5	0.37
MEDIAN VALUE	0.22	0.9	0.3	0.57	0.85	0.72	0.28	1.18	0.45	1.38	1.4	1.4
75 PERCENTILE	2.2	3.65	2.37	6.02	3.85	4.53	3.18	6.28	4.68	8.4	7.07	7.32
90 PERCENTILE	10.3	12.72	10.9	24.7	17.23	22.25	21.43	22.45	22.45	30.8	29.27	28.7
95 PERCENTILE	23.2	24.27	24.1	59.88	41.72	51.45	77.2	63.27	74.37	53.92	59.2	52.25
MAXIMUM VALUE	845.27	823.18	845.27	976.85	854.02	976.85	893.08	180.53	893.08	294.55	272	294.55
TOTAL HOURS (DURATION)	23 693	7 032	32 726	29 095	15 252	56 656	7 411	2 176	9 911	3 039	1 822	5 018
TOTAL NUMBER OF OUTAGES	2 985	714	3 879	1 747	1 428	3 966	413	201	647	214	131	390

NOTES:

(1) EXCLUDES COMMON MODE OUTAGES

(2) ANY OUTAGES OF DURATION LONGER THAN 1,000 HOURS WERE EXCLUDED IN COMPILING DURATION STATISTICS (SEE BELOW)

(3) "SCHEDULED OUTAGES" SHOWN IN TABLE 18 ARE INCLUDED IN THIS TABLE

(4) THIS COLUMN IS THE SUM OF "LINE-RELATED", "TERMINAL-RELATED" AND "UNKNOWN" PROBLEM-TYPE OUTAGES

	OUTAGES LONGER THAN 1,000 HOURS											
TOTAL HOURS (DURATION)	55 581	17 339	74 916	44 345	11 852	130 743	0	4 517	22 038	0	0	0
TOTAL NUMBER OF OUTAGES	7	5	13	5	2	15	0	2	3	0	0	0

Table 23. Distribution of Primary Outages with Respect to Outage Type, Degree of Outage, and Effect of Outage, by Voltage.

OUTAGE TYPE	230 KV	345 KV	500 KV	765 KV
SUSTAINED - AUTOMATIC	31.60%	6.80%	12.47%	7.56%
SUSTAINED - FORCED MANUAL	2.61%	6.72%	9.75%	6.90%
SUSTAINED - NOT SPECIFIED	1.34%	5.85%	0.17%	1.56%
MOMENTARY - AUTOMATIC	17.50%	14.33%	25.33%	11.70%
MOMENTARY - FORCED MANUAL	0.55%	0.34%	0.07%	0.00%
MOMENTARY - NOT SPECIFIED	0.30%	2.67%	0.00%	0.66%
PLANNED	46.09%	63.30%	52.21%	71.62%
TOTAL PERCENT	100%	100%	100%	100%
TOTAL NUMBER OF OUTAGES	10 946	20 563	2 902	2 435

DEGREE OF OUTAGE (SUSTAINED)	230 KV	345 KV	500 KV	765 KV
COMPLETE	95.66%	97.97%	91.23%	100.00%
PARTIAL	0.85%	1.06%	8.77%	0.00%
NOT CLASSIFIED	3.49%	0.98%	0.00%	0.00%
TOTAL PERCENT	100%	100%	100%	100%
TOTAL NUMBER OF OUTAGES	3 892	3 981	650	390

EFFECT OF OUTAGE (SUSTAINED)	230 KV	345 KV	500 KV	765 KV
CASCADING	0.00%	0.00%	0.00%	0.00%
LOSS OF GENERATION	0.62%	0.08%	0.00%	0.00%
LOSS OF TERMINAL BANK	0.00%	0.00%	0.00%	0.00%
LOSS OF LOAD	3.47%	0.08%	1.85%	0.00%
INSTABILITY	0.10%	0.00%	0.00%	0.00%
LOSS OF INTERCONNECTION	2.24%	4.14%	8.92%	0.00%
OVERLOAD	0.00%	0.00%	0.77%	0.00%
LINE DAMAGE	2.80%	0.03%	1.54%	0.00%
EQUIPMENT DAMAGE	0.05%	0.05%	7.54%	0.00%
CONTROLLED LOAD SHED	0.03%	0.00%	0.00%	0.00%
BLACKOUT	0.00%	0.05%	0.00%	0.00%
LOSS OF OTHER CIRCUITS (<230KV)	0.59%	0.38%	0.00%	3.33%
NO ADVERSE EFFECT	40.34%	15.10%	48.46%	43.85%
NOT CLASSIFIED	49.77%	80.11%	30.92%	52.82%
TOTAL PERCENT	100%	100%	100%	100%
TOTAL NUMBER OF OUTAGES	3 892	3 981	650	390

* NOTE: EXCLUDES COMMON MODE OUTAGES

Table 24. Mode of Restoration as a Percent of Total Number of Primary Outages.

	230KV				345KV				500KV				765KV			
	FORCED		PLANNED		FORCED		PLANNED		FORCED		PLANNED		FORCED		PLANNED	
	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.
AUTOMATIC	31.45%	2 05%	0.10%	0.18%	39.84%	2.00%	1.05%	0.21%	52.42%	11.68%	0.26%	0.00%	41.39%	0.29%	1.26%	0.00%
MANUAL/SUPERVISORY	1.00%	32 25%	2.50%	66.87%	0.42%	35.86%	1.38%	95.59%	0.58%	29.99%	0.53%	82.28%	0.00%	52.24%	0.06%	98.68%
REPAIR/REPLACE	0.17%	5 41%	1.57%	5.57%	0.04%	4.32%	0.01%	0.26%	0.07%	4.04%	0.00%	7.80%	0.00%	0.58%	0.00%	0.00%
UNKNOWN	1.42%	26 25%	0.10%	23.12%	6.94%	10.58%	0.02%	1.49%	0.07%	1.15%	0.00%	9.13%	2.17%	3.33%	0.00%	0.00%
TOTAL # OUTAGES	5 901		5 031		7 546		12 972		1 387		1 512		691		1 744	
TOTAL PERCENT	100%		100%		100%		100%		100%		100%		100%		100%	

* NOTE: EXCLUDES COMMON MODE OUTAGES

inserted in this field to indicate "Not Classified" only when it was obvious that a utility uniformly made no attempt to classify the type of fault. If a utility had occasionally a non-blank code in this field, it was assumed that the data submitter was consistent and that a blank field was intended to mean 'No Fault.'

COMPARISON WITH 1965 SURVEY

The 1949, 1965 and the 1985 surveys had common basic objectives: the pooling of transmission line outage experience to gain a better understanding of outage occurrence rates and causes (especially of rare events), the correlation of line performance with design, and, in general, the promotion of formal collection of circuit outage and exposure history.

Unlike the previous two surveys, the 1985 survey partitioned initiating problems into "Line-Related" and "Terminal-Related" in an attempt to develop outage rates that were functions of circuit length and number of circuit terminals, respectively. Whereas the 1949 and 1965 surveys classified outages only as "Temporary" or "Permanent," the 1985 survey requested outage start and end times to provide a basis for estimating average outage duration. The 1985 survey also collected data on planned outages.

Table 25 provides sample comparisons of the results of the 1965 and 1985 surveys. (A similar table could be developed using 1949 survey results.) The first column provides direct comparisons of the response to the survey, the fraction of the forced outages that were "Sustained" (assumed equivalent to

"Permanent" in the 1965 survey), and the fraction of forced outages that were caused by lightning. (Lightning continued to be the prevalent cause of outage.)

The comparisons in the second column of Table 25 required some manipulation of the data collected in the 1965 survey to ensure a common basis. Because the exposure data for the 1965 survey were expressed only in circuit-mile-years, comparison must be confined to primary forced outage rates as a result of line-related problems. This requires that outages initiated by terminal-related problems be removed from the 1965 results.

In the calculation of the lightning outage rates in Table 24, it was assumed that the outages of "Unknown" problem type collected in the 1985 survey (Table 18) were line-related. These were then combined with

Table 25. Sample Comparisons of the Results of the 1985 and 1965 Surveys.

	1985 Survey	1965 Survey
Time Period Surveyed (1)	21 Years	15 Years
No. of Circuits Involved		
At 230kV	1 071	325
At 287kV	0	10
At 345kV	664	51
At 500kV	204	0
At 765kV	93	0
Total	2 032	386
Circuit Exposure (Mile-Years)		
At 230kV	232 454	145 645
At 287kV	0	10 678
At 345kV	232 949	14 743
At 500kV	78 364	0
At 765kV	39 945	0
Total	583 712	171 066
No. of Primary Forced Outages (2) (Events)		
At 230kV	5 901	1 659
At 287kV	0	213
At 345kV	7 546	896
At 500kV	1 387	0
At 765kV	691	0
Total	15 525	2 568
No. of Primary Planned Outages (Events)		
Total	21 259	0
Fraction of Primary Forced Outages That were "Sustained" (3)		
At 230kV	66%	34%
At 287kV	--	24%
At 345kV	53%	19%
At 500kV	47%	--
At 765kV	56%	--
Overall	57%	29%
Fraction of Primary Forced Outages Caused by Lightning		
At 230kV	22%	36%
At 287kV	--	13%
At 345kV	22%	64%
At 500kV	27%	--
At 765kV	24%	--
Overall	22%	42%

	1985 Survey	1965 Survey
Lightning Outage Rate (4) (Per 100-Mile-Year)		
At 230kV	0.556	0.409
At 287kV	--	0.262
At 345kV	0.698	3.039
At 500kV	0.473	--
At 765kV	0.458	--
Overall	0.596	0.627
Forced Outage Rate (5) (Per 100-Mile-Year)		
At 230kV		
Momentary	0.714	0.648
Sustained	1.287	0.301
Total (6)	2.000	0.971
At 287kV		
Momentary	--	1.461
Sustained	--	0.468
Total (6)	--	1.939
At 345kV		
Momentary	0.869	3.276
Sustained	0.752	0.692
Total (6)	1.621	3.988
At 500kV		
Momentary	0.853	--
Sustained	0.527	--
Total	1.380	--
At 765kV		
Momentary	0.471	--
Sustained	0.536	--
Total	1.008	--
Phase-to-Ground Fault Rate (5) (Per 100-Mile-Year)		
At 230kV	0.713	0.548
At 287kV	--	0.365
At 345kV	0.510	3.147
At 500kV	0.902	--
At 765kV	0.418	--
3-Phase & 3-Phase-to-Ground Fault Rate (5) (Per 100-Mile-Year)		
At 230kV	0.037	0.010
At 287kV	--	0.009
At 345kV	0.018	0.163
At 500kV	0.019	--
At 765kV	0.000	--

Notes:

(1) Time Period Surveyed: 1985 Survey, 1/65-12/85; 1965 Survey, 1/50-12/64.

(2) The event count for the 1985 survey excludes common-mode outages.

(3) Assumes that all outages of duration class "Not Reported" in the 1965 survey were sustained in nature.

(4) Assumes that all lightning outages in the 1965 survey were line-related. Includes "Line-Related" and "Unknown" and excludes "Terminal-Related" lightning problem types assembled in the 1985 survey.

(5) To approximate outage rates due to line-related problems, 1965 outage rates are adjusted to exclude terminal-related outages by removing those caused by "Terminal Equipment", "Undesired Relay Operation" and "Personnel Error". The 1985 outage rates exclude "Terminal-Related" and "Unknown" problem types.

(6) Includes those events for which Outage Type (Momentary/Sustained) was "Not Reported" in the 1965 survey.

those known to be "Line-Related" to calculate the line-related rate. In the results of the 1965 survey, all lightning outages were assumed to have been line-related in the calculation of a comparable rate.

To calculate forced outage and fault rates as functions of circuit length, the following assumptions were made. On the 1985 side, only the line-related outages were considered. (If the outages of "Unknown" problem type were also assumed to be line-related, the outage rate would increase--especially for 345kV.) On the 1965 side, the assumption was made that outages caused by "Terminal Equipment Failure," "Undesired Relay Operation" and "Personnel Error" were terminal-related, and that all other outages were line-related. These were subtracted from the total outage count before calculating the forced outage rate as a function of circuit length.

The sample comparison of the results of the two surveys, as presented in Table 25, suggests the following shifts in outage characteristics. In more recent years, the fraction of primary forced outages that were sustained has increased, while the fraction of primary forced outages that was caused by lightning has decreased. Lightning outage rates, however, appear to have increased in the 1985 survey (recognizing that the 345kV sample in the 1965 survey was small). The line-related primary forced outage rates also appear generally to have increased (an increase that would be even more pronounced if some fraction of the outages of "Unknown" problem-type in Table 18 were assumed to be line-related).

CONCLUSIONS AND RECOMMENDATIONS

On Meeting Survey Goals

In the Introduction, six goals adopted by the Working Group are listed. The first three goals relate to estimating failure rates and restoration times and gaining a better understanding of causes and effects. The results reported in this paper address all three goals with the exception of summarizing the causes of the related multiple outage events. Because of the multiplicity of outage combinations, an event-by-event study is required to adequately generalize the nature of the causes. Further effort in this area will be guided by the interests and concerns of the readers as expressed in the discussion of this paper.

To expedite the publication of the basic survey data, the fourth goal of exploring the correlation of circuit design characteristics with circuit outage rate has been left to a future effort. The nature and depth of this effort will again depend on the level of interest displayed by the readers.

The degree of success in meeting the fifth goal of updating results and determining how performance has changed since the last survey is difficult to assess. The comparison attempted in Table 25 is based on surveys of two different populations. Although the goals were similar, the circuits and their environments were not. The general manner of collecting and recording outage data may have also been different.

With regard to the sixth goal of fostering the uniform and consistent collection of transmission line outage and exposure data, the 1985 survey process was a success. The Transmission Outage Data Submission Guide, along with its companion Circuit Characteristic Data Submission Guide, developed by the Working Group, served as a model and starting point for a number of utilities that had not previously formally collected the data.

The Next Survey

As more utilities institute transmission data collection systems, and as the data are standardized and pooled on a regional basis, the justification for and value of pooling data over a broad and diverse geographic area such as North America falls into question. It is likely that, by the year 2000, most of the utilities that responded to the 1985 survey will be contributing transmission data to regional databases. Because of the increasingly evident inadequacies of deterministic approaches to ensuring the adequacy of transmission systems, many other utilities will have likely implemented data collection systems. Because of these tendencies, the task of updating this survey will be less formidable, and more likely to succeed in satisfying goals similar to those of the 1985 effort. If, however, by the year 2000, many utilities remain uncommitted to the systematic collection of transmission data, then the new survey will collect data that would not otherwise have been assembled, and, as in the past, utility participation in data collection will have been encouraged and advanced.

Whether the effort be focused on the development of a regional database, or on a survey of North America, there should be an effort to better capture and characterize the nature of related multiple outage events. An unfortunate aspect of the 1985 survey was that large blocks of outage data were reported totally as single-circuit independent events.

Time taken in careful preparation of a future survey will pay a significant dividend when the time arrives to analyze the data. Spend time investigating the nature of available data, so that the request for data will not require a heroic effort in response. Care should be taken to clearly define terms and provide codes for all possible situations. Never use an blank field as a response option. Finally, avoid, if possible, undertaking the conversion of a contributing entity's data to the desired format. This task is best done by someone with an intimate and working knowledge of the original data collection system.

WORKING GROUP MEMBERSHIP

R. B. Adler, Chair	Philadelphia Electric
P. F. Albrecht	Consultant
G. K. Bell	Pacific Gas & Electric
M. P. Bhavaraju	Public Service Electric & Gas
B. D. Caldwell	Ontario Hydro
K. R. Chakravarthi	Southern Company Services
S. L. Daniel, Jr.	Southern Company Services
J. H. Doudna	Power Technologies, Inc.
C. R. Heising	Industrial Reliability Tech
A. A. Iannacone	Atlantic Electric
M. G. Lauby	Electric Power Research Institute
R. P. Ludorf	Northeast Utilities Service Co.
P. C. Masic	Tennessee Valley Authority
A. W. Schneider, Jr.	Commonwealth Edison
K. S. Shah	Union Electric
H. A. W. Volpe	Bonneville Power Administration
T. S. White	Mid-Continent Area Power Pool
H. H. Yan	Philadelphia Electric

ACKNOWLEDGEMENTS

The authors wish to thank the members of the Working Group and of it sponsor, the General Systems Subcommittee, for their enduring support in the development and implementation of the survey, the review and analysis of the data, and the production of this paper and its two predecessors. The Working Group is indebted to the utilities and systems that have

entrusted us with their data, and to the individuals who coordinated the voluntary data submission. We also wish to express our gratitude to our respective organizations for supporting this activity. Finally we wish to acknowledge the dedicated assistance of Ms. Teresa Glaze of Southern Company Services in the development of the Tables presented in this paper.

REFERENCES

[1] Electric Power Research Institute, Bulk Transmission System Component Outage Data Base, Report EL-1797, April, 1981.

[2] AIEE Committee Report, "Report on the Joint AIEE-EEI Subject Committee on Line Outages," AIEE Transactions on Power Apparatus and Systems, Vol. 71, pp. 43-61, January, 1952.

[3] IEEE-EEI Committee Report, "Extra High Voltage Line Outages," IEEE Transactions on Power Apparatus and Systems, Vol. 86, pp. 547-562, May, 1967.

[4] IEEE Task Force on the Requirements for the Survey of Line Outage Data, "IEEE T&D Working Group on Statistics of Line Outages: Background, Status and Prospects," Proceedings of the 14th INTER-RAM Conference for the Electric Power Industry, Toronto, Ontario, pp. 255-262, May 26-29, 1987.

[5] IEEE Standard Terms for Reporting and Analyzing Outage Occurrences and Outage States of Electrical Transmission Facilities, IEEE Std. 859-1987.

[6] IEEE Task Force on Line Design Characteristics, Working Group on Statistics of Line Outages, "An IEEE Survey of Transmission Line Population and Design Characteristics," IEEE Transactions on Power Delivery, Vol. 6, pp. 1934-1945, October, 1991.

DISCUSSION

RONALD O. GUNDERSON, Nebraska Public Power District, Hastings, Nebraska: The authors are to be commended for the effort in this immense task. The authors state that a significant number of terminal related outage records have been removed from the outage database because of irreconcilable data deficiencies. Not including these outages in the calculation of outage rates will lead to outage rates which are significantly lower than the actual outage rates of the lines. Would the authors indicate how many outage records were excluded and some examples of the type of irreconcilable data deficiencies which occurred.

Historically, outage rates for terminal related outages have been expressed in terms of outages per terminal year. The assumption is made that the number of terminal related outages is directly proportional to the number of terminals. It would be interesting to know if the data supports this assumption. Is the outage rate per terminal year for two terminal lines essentially the same as that for three terminal lines or four terminal lines? Or are the outage rates for multiple terminal lines greater because of the increased complexity of the associated protection systems and the possibility of incorrect operations? Similar questions can be asked of the bus configuration at each terminal. Reference [1] concludes that outage rates and durations for terminal related outages are different for different bus configurations. Can the task force give estimated outage rates for different bus configurations? Future collection efforts should collect data on the type of bus configuration at each terminal.

The goal of correlating circuit design characteristics with circuit outage rates is a worthwhile goal. Utilities need to know how the different design characteristics such as single circuit line vs. double circuit line and different types of construction material and configuration affect the performance of transmission lines. This information becomes more important as the transmission system becomes more heavily loaded and outages become more critical.

The industry needs to better understand what factors influence transmission line performance. By collecting data over a large area with the same format, analyses can be performed which may improve this understanding. For example, do relatively short lines in urban areas have the same performance characteristics as relatively long lines in rural areas? What is the effect of different climates on outage performance? Reference [2] describes an outage data collection format which was developed by two NERC regions and is being utilized by them. This format collects characteristic data on different types of basic construction, terminal configuration, and common exposure. Information is collected for related outage events also.

REFERENCES

[1] M. G. Lauby, D. D. Klempel, C. G. Dahl, R. O. Gunderson, E. P. Weber, P. J. Lehman, "The Effects of Terminal Complexity and Redundancy on the Frequency and Duration of Forced Outages", *IEEE Transactions on Power Systems*, Vol. PWRS-2, No. 4, Nov. 1987, pp.856-862.

[2] Transmission Outage Task Force of the Mid-America Interconnected Network, Transmission Reliability Task Force of the Mid-Continent Area Power Pool, M. G. Lauby, "Joint Development of Consistent Bulk Transmission Outage Reporting and Analysis Procedures by Two NERC Regions", *IEEE Transactions on Power Systems*, Vol. 4, No. 2, May 1989, pp. 507-516.

M. Oprisan (Canadian Electrical Association, Montreal, Quebec, Canada): I wish to compliment the authors, members of the Working Group on Statistics of Line Outages, on the excellent and comprehensive analysis provided in their paper. From personal experience I know what a formidable task it is to compile such a vast amount of information, ensure the consistency of data and try to derive meaningful statistics which could be of use to the contributors.

The Canadian Electrical Association has collected transmission equipment outage data since 1978 and I have included below, for comparison, a portion of the report covering the 5-year period 1986-1990 for 230 kV transmission lines, both momentary and sustained outages.

Summary of Transmission Line Statistics for Line-Related Sustained Forced Outages

Voltage Classification	Kilometre Years (km.a)	Number of Outages	Total Time (h)	Frequency (Per 100 km.a)	Mean Duration (h)	Unavailability (%)
200-299 kV	171,104	929	11,502	0.5429	12.4	0.077

Summary of Transmission Line Statistics for Line-Related Momentary Forced Outages

Voltage Classification	Kilometre Years (km.a)	Number of Outages	Frequency (per 100 km.a)
200-299 kV	171,104	1,008	0.5891

Summary of Transmission Line Statistics for Terminal-Related Sustained Forced Outages

Voltage Classification	Terminal Years (a)	Number of Outages	Total Time (h)	Frequency (Per a)	Mean Duration (h)	Unavailability (%)
200-299 kV	4,870	658	3,070	0.1351	4.7	0.007

With regard to momentary and sustained outages, I noticed on page 3 of your paper under Data Summaries that a momentary outage is defined as having a restoration time of less than or equal to one minute. However, a sustained outage is defined as having a restoration time equal to or greater than two minutes. The CEA system defines a sustained outage as having a restoration time greater than one minute. Was the restoration time between one and two minutes purposefully excluded from your definitions?

On Table 18, page 4, among Defective Equipment Primary Causes you list Circuit Breakers, Transformers, Shunt Reactor Banks, etc. I was wondering if these should be actually lumped together with the transmission lines and if by doing so one does not get a somewhat distorted image of transmission line performance. In the CEA system these pieces of power equipment are analyzed separately as components of the transmission system.

I should also note that all Canadian utilities have agreed, from the beginning, to submit the transmission component inventory and outages in full and in a consistent format which resulted in meaningful and useful statistics based on a large database. This can be partly attributed to the fact that the number of utilities involved is rather small even if some of them are large in size. This comment applies to the last paragraph of

the "On Meeting Survey Goals" on page 12 and I should add that as far as the Canadian utilities are concerned the interest has been and I believe will always be there for collecting this type of information. I suspect that the same will be true for the U.S. utilities.

In concluding, I would like to know how you see the usefulness of such a survey conducted every 15–20 years. Surveys were conducted in 1949, 1965, 1985 and you seem to be talking about the next one in 2000. You will certainly appreciate the reason for this question since, as I mentioned before, CEA has produced such surveys annually since 1978.

Manuscript received January 26, 1993.

MAIN Transmission Outage Task Force: G. A. Johnson, chairman (Central Illinois Public Service Co.); **E. C. Pfeiffer** (Union Electric Co.); **P. B. Burke** (Commonwealth Edison Co.); **D. L. Smith** (Wisconsin Public Service Corp.); **A. W. Schneider, Jr.** (MAIN Coordination Center): The Mid-America Interconnected Network (MAIN) Transmission Outage Task Force was among the participants in the survey leading to this paper; thus we appreciate first hand the difficulty of providing certain requested data items which were not in our computer file of EHV transmission outages. The Data Analysis Task Force has succeeded beyond our expectations in providing "typical" performance measures which can help the industry to prioritize development of analytical tools. In addition, this survey has stimulated revisions to MAIN data collection procedures so that relevant characteristics of EHV outages are recorded permanently in an easily retrievable form.

From time to time suggestions are made to establish an ongoing collection of EHV transmission outage data covering all of North America. This would be similar to the GADS collection of generating unit outage data. This would be of questionable value because indices computed from such data would probably be poor predictors of the performance of any particular line. There are at least two reasons for this. First, overhead lines operate in very diverse environments, compensated to some extent by the line design. Second, the "vintage" of a transmission line is much more difficult to establish than that of a generating unit, as old lines are cut and extended to new terminals to meet new system requirements.

However, periodic efforts such as this paper stimulate the trend toward complete data collection on outages which is essential to make rigorous estimates of future performance, as in comparing the reliability of alternative designs.

The Data Analysis Task Force has presented forceful conclusions which should be carefully considered in creating or revising regional data collection schemes. The resulting data will be greatly enhanced, and future pooling of data will require much less effort and fewer interpretations and assumptions.

Indices computed using the methods of this paper will be less adequate for lines of more complex topology, such as the 115 kV through 161 kV transmission lines used to supply distribution substations and industrial customers from EHV points of supply. These lines may have greater impact on the reliability of supply to customers, because there is often a lower level of redundancy. They are also subject to frequent sectionalizing and switching. Does the Task Force plan to recommend data collection methods to develop useful performance indices for such lines?

Manuscript received February 16, 1993.

J. Endrenyi and L. Wang (Ontario Hydro, Toronto, Canada): One of the purposes of this survey is to address the need for line outage data in probabilistic modelling for planning and operation. The survey results reported in this paper involves the pooling of line outage data submitted by utilities in the U.S. and Canada. A pertinent question to ask is: can the pooling process be carried out without considering such factors as homogeneity in line design and operating environment? Similar questions have been asked in the pooling of generating unit data, and these questions are now being addressed by the Task Force on Generating Unit Data Pooling of the Application of Probability Methods Subcommittee. Unconstrained pooling may reduce the usefulness of the information.

We noticed that in Table 18 the weather-related outages are separately identified. This is, however, not sufficient information to calculate separate good- and severe-weather outage rates required in some reliability models. To obtain these rates, the average duration of severe weather periods would also be needed. Yet, this information is dependent on the region and probably cannot be pooled. Is any extension of the work foreseen to address this problem?

Finally, we would like to congratulate the members of the Data Analysis Task Force for their effort and valuable contributions in compiling and analyzing a tremendous amount of line outage data.

Manuscript received February 22, 1993.

HELENANN VOLPE AND BRIAN SILVERSTEIN (Bonneville Power Administration, Portland, OR). We commend the Data Analysis Task Force for the excellent job that they did in gathering and analyzing the large volume of outage data that was collected. The results are good indicators of large scale trends in outage rates for transmission lines operating at or above 230-kV.

Would the authors please expand on the "irreconcilable data deficiency" that leads to the caution not to draw conclusions about the ratio of line-related to terminal-related outages.

Reference was made, both in the paper and at the presentation, to the large amount of unanalyzed design related material in the data base [6] and the question arose as to what should be done with it. Perhaps some exploratory multi-variate analysis will point to those design parameters which warrant further investigation, either by this group or by others.

One possibility for future work is to join with the Working Group on Performance Records under the Application of Probability Methods Subcommittee, who have an ongoing effort on Data Pooling for Generators. With contributor permission, and removing utility identification, the data could also be made available to researchers in computer readable form.

Through the efforts of the Task Force, the authors now have a comprehensive understanding of the strengths and weaknesses of the data collection format that was used in this project. Some suggestions are made for

improvement in the section on The Next Survey. If data subsequent to 1985 can be collected in a materially similar form, it may be possible to observe trends in outage rates. This common basis for comparison will make the analysis more valuable.

Manuscript received February 22, 1993.

R. J. Ringlee (Power Technologies, Inc., Schenectady, NY): Appreciation and compliments are due the Data Analysis Task Force for its success in presenting results much more comprehensive than preceding surveys, results that represent a significant contribution to the overhead line performance data base and which should be of value in improving estimates of outage rate and restoration for overhead lines. Collection of data on multiple outage events is a significant addition to the data base. Data on the likelihood of these events are essential for bulk power system reliability prediction and knowledge of their likelihood is a necessary input to rational formation of reliability criteria for design of lines and stations. For example, Table 20 indicates that a significant fraction of the multiple outages were identified as arising from common-terminal common mode. Table 18 indicates that nearly one third of the sustained outages for 500 and 765 kV circuits were identified as terminal related. Data in both Tables prompt the question of root cause for the high numbers of terminal-related outages and raise the opportunity to explore the reliability benefit/cost of improved station equipment performance and alternative station designs.

The step of exploring the correlation of circuit outage rate with line design characteristics is of fundamental importance; may the Task Force receive the encouragement it seeks to continue its efforts in this direction.

The authors have indicated that trend analysis should not be attempted by comparison of the data between successive surveys owing to the differing data sets involved. The discussor agrees if the comparison were to be made between statistics representing the aggregate performance of all circuits of a given voltage. There's an alternative that might be considered if the information on specific circuits were available in successive surveys: paired comparisons. Circuits that appear in both surveys would be candidates for making estimates of trends. In like manner, paired comparisons could be made with the circuit data in the latest survey to compare the effect of design by pairing circuits of dissimilar design but located in similar geographical areas and using the data that span the same period.

Manuscript received February 24, 1993.

T. E. McDermott (Power Technologies, Inc., Pittsburgh, PA): The task force has effectively presented a large amount of data on transmission outages, and this information should be valuable to the industry. Other investigators may wish to pursue goal 4 of the survey, by correlating outages with certain design parameters. Would it be possible to maintain the raw data presented in this paper and in [6], in electronic format, under the auspices of the General Systems Subcommittee?

Many of the reported outages were caused by lightning. The IEEE Working Group on Estimating the Lightning Performances of Transmission Lines has a public-domain computer program (FLASH) to predict the lightning performance of overhead lines. With the outage data in this paper and the design data in [6], it may be possible to validate or improve the models in FLASH. The Electric Power Research Institute also has a program (MULTIFLASH) that offers a prediction of multi-phase and/or multi-circuit outages. The data collected by this task force would be very useful in analyzing the results of both programs, if the data were kept accessible in an electronic format.

Manuscript received March 1, 1993.

V. S. Rashkes (former Chief of EHV Field Tests Division of Electric Power Research Institute, Moscow, Russia; now with General Electric at the EPRI High Voltage Transmission Research Center, Lenox, MA): Statistical data on the service performance of HV/EHV transmission lines were collected and analyzed also in the USSR during many tens of years. The high interest of power engineers in each new publication on this subject demonstrates that they recognize very clearly how important and beneficial it is to use service experience for future improvements in transmission reliability.

For American power engineers it would be of interest to compare their own service experience published in the discussed paper with the Soviet one which is summarized in recent publications [1–3].

General characteristic of Soviet transmission network. The territory of the former USSR is much larger than that of the US (22.4 and 9.4 million sq. km respectively), its population exceeds the US population only by 10% (284 and 245 million people in 1988), so the medium density of population was much lower than in the USA. Electric energy production was significantly less than that of the USA and in 1990 reached 1.8 million GW.hours. As a result, main power flows were less than in the USA, and the HV transmission network was not so dense and multicircuit transmission was rare. Nevertheless the total length of HV transmission lines was very large and increased fast (in thousands km):

in 1960- about 150, in 1970- 450, in 1980- 780, in 1990- 1100.

Total length of EHV lines—345 kV and above—was (in thousands km):

in 1960- about 5, in 1970- 28, in 1980- 55, in 1990- 98.

The voltage level of 400–500 kV in Soviet transmissions was reached in 1956–62, 750 kV- in 1966, 1150 kV- in 1985, and in 1990 there were in operation (in thousands km):

330 kV- about 32, 500 kV- 55, 750 kV- 10, 1150 kV- 1.

All Soviet 750 and 1150 kV lines, as well as the absolute majority of 500 kV lines are single circuit. Reserves in network transmitting capacity and in generating capacity are small, so for the Soviet power utilities is very important to reach high service reliability, especially for EHV lines. Progress in line design, proper choice of insulation and overvoltage protection, wide application of high-speed autoreclosing, especially single-pole, efforts to maintain necessary level of service and repair works permitted to reach this goal. Service experience in the USSR was analyzed on a regular base (annually). This helped considerably in improving reliability.

Service experience data. For analysis in [1] author used data of 1981–1985 with total volume about 2.6 million km.year. These data were compared with earlier published [4–7], which covered about 0.3 million km.years during 1959–1980 but were for different regions of the USSR.

The specific number of Soviet line outages for each rated line voltage were (per 100 km.years):

For lines	110 kV	150 kV	220 kV	330 kV	500 kV	750 kV
In 1981–1985	3.0	1.8	1.5	1.5	0.6	0.2
In [4–7]	1.5–3.5	–	0.5–2.0	1.5–3.2	0.58	

The spread in the data of [4–7] is caused by regional differences in insulation contamination, lightning protection etc., so the averaged figures from the more recent survey based on a bigger observation volume are more reliable. For 1150 kV lines, their total length and observation period are too small for dependable evaluation, but preliminary results show that the specific number of outages is about 0.1 per 100 km.year. It is of interest to characterize the reasons of outages for EHV lines. According to [8, 9] the causes of outages of Soviet 500 and 750 kV lines are (in % of total number of outages):

	500 kV	750 kV
Defects of manufacturing and maintenance	17.9	13.7
Ice, snow, conductor galloping, etc.	11.6	3.8
Wind	9.3	20.6
Lightning	12.7	20.0
Flashover of contaminated insulation	4.2	8.6
Fire, mechanical damages by outgoing people and transport	16.6	13.8
Unknown reasons	27.7	17.5

Specific number of outages in the Soviet network is in satisfactory agreement with previously published American and Canadian data including [10].

One of the goals for the analysis performed was to check the effectiveness of high-speed autoreclosing as a very inexpensive measure to improve line reliability. The percentage of arcing faults which could be potentially cleared by high-speed reclosing could be assessed only approximately because faulty phase voltage was not always of sufficient size to determine from the oscillograms of the failure if short circuit was through arc. So probability of arc faults was evaluated as:

110–220 kV- 0.6–0.9, 330 kV- 0.7–0.85, 500–750 kV- 0.65–0.75

(higher values are applicable to lines with higher specific number of outages due to lightning storms or polluted insulation flashovers). Arc faults may be created also by wind, conductor galloping, fire, outgoing vehicles' movement etc., so the incidence of arc faults is in good agreement with the above mentioned statistical reasons of trippings. Possibly, the percentage of arc faults is even higher because special analysis showed that unsuccessful high-speed reclosings originally supposed to be metal or tree short-circuits were associated with too small dead times or with multiple flashovers of contaminated insulation in unfavorable weather conditions.

The proportion of single-phase faults in the total number of line trippings increases with rated voltage and, correspondingly, with growing tower dimensions:

220 kV-0.6, 330 kV-0.8, 500 kV-0.92, 750 kV-0.98.

This means that for EHV lines single-pole high-speed reclosing becomes the main mode of reclosing. Really, although composite single- and three-phase reclosing devices are in common use in the USSR, the single-phase mode of their operation is predominant in the 330-500 kV network and is practically the only one for 750 kV lines. For 750 kV lines three-phase high-speed autoreclosing works only at mistaken trippings of the line.

Success of high-speed reclosing slightly decreases with EHV rated voltage and is somewhat less than in the USA:

	110 kV	220 kV	330 kV	500 kV	750 kV
Single-phase in the USSR	0.58	0.73	0.72	0.62	0.52
Single- and 3-phase total in the USSR	0.75	0.76	0.75	0.62	0.52
Single- and 3-phase total in USA [11]	0.62	0.70	0.85	0.77	0.67.

This primarily occurs because fault rate sharply falls with rise of rated voltage and therefore various defects that autoreclosing cannot correct become more pronounced.

It could be seen that such a simple measure as single-phase high-speed autoreclosing provides continuity of power supply through EHV lines in a half or three quarters of the outages.

Dead time for the Soviet EHV lines usually equals, in dependence of secondary arc current, 0.6–2.5 sec. Automatic devices for high-speed reclosing worked properly in 99.8% of cases. Information about reliability of other kinds of relay protection and automatic devices is given in [3].

A small specific rate of outages in 750 kV lines together with high enough efficiency of high-speed reclosure led to the situation when one tripping of such line due to its failure is statistically as frequent as one tripping due to the failure of substation equipment and 0.5–1 tripping due to malfunctioning of relay protection devices or mistakes of service personnel. The same situation was found in Canada [10]. Such data show the practical necessity of paying attention to equipment reliability, transmission schemes and personnel training.

References

[1] V. S. Rashkes. Summary and analysis of operating data on the effectiveness of SPAR on EHV lines and experimental data on arc extinction times. Elektricheskie stanzii [Power Plants], 1989, #3 (in Russian).

[2] N. N. Belyakov, V. L. Volchek, V. V. Ilyinichnin et al. Application of single-phase autoreclosing in a complex EHV network containing 1200 kV transmission lines. CIGRE, 1990, #34-207.

[3] V. V. Ilyinichnin, K. V. Khoetzian, V. F. Lachugin et al. Service experience and field tests summarizing the protection and control devices improvement in EHV-UHV transmissions. CIGRE, 1992, #34-102.

[4] A. S. Maikopar. Arc faults on overhead transmission lines. Energia Publishing House, Moscow, 1965 (in Russian).

[5] N. N. Beljakov, K. A. Brinkis, V. S. Rashkes. Correction SPAR dead-times for 330 kV lines using their service experience. Elektricheskie stanzii, 1982, #3 (in Russian).

[6] V. V. Bochkowski, B. I. Udod. Analysis of outages reasons for 110–330 kV lines. Elektricheskie stanzii, 1984, #4 (in Russian).

[7] N. A. Melnikov, S. S. Rokotjan, A. N. Sherenzis. Electric designing of 330–500 kV overhead transmission lines. Energia Publishing House, Moscow, 1974 (in Russian).

[8] A. S. Zelichenko, B. I. Smirnov. The mechanical designing of EHV overhead transmission lines. Energoizdat Publishing House, Moscow, 1981 (in Russian).

[9] V. V. Bourgsdorf, T. B. Turskaya. Service experience for 750 kV transmission lines. Elektricheskie stanzii, 1988, #5 (in Russian).

[10] Forced outage performance of transmission equipment for the period January 1, 1978 to June 30, 1983. Montreal, Canadian Electrical Association, 1984.

[11] Automatic reclosing of transmission lines. IEEE Power System Relaying Committee report. IEEE Trans. on PAS, 1984, v.103, #2, pp. 234–245.

Manuscript received March 1, 1993.

R. B. ADLER, C. R. HEISING, T. S. WHITE, M. G. LAUBY, S. L. DANIEL JR., R. P. LUDORF: We hasten to thank the discussers for their expressions of appreciation for the efforts of the Working Group on Statistics of Line Outages. We thank them also for their

thoughtful and provocative comments and questions. Their discussion has motivated us to explore further the correlations and implications of the line outage and design history entrusted to us.

Several discussers raised questions on the nature of the data deficiencies that prompted the Data Analysis Task Force (DATF) to discard data. This by and large arose when we had to convert data from one form to another. In these cases, the data were submitted in a format different from the requested format. In several cases, with the help of the data submitter, the DATF developed a conversion program for both the outage and exposure data. In some cases, however, certain essential data was absent. One particularly troublesome type of conversion is from a database developed by a collection system whose primary purpose is to estimate component outage and repair rates. The IEEE format, however, is oriented to the development of outage and repair rates for the transmission circuit as a unit [1].

Concerns about the value of pooled data are ever present. Pooling of non-homogenous data always introduces questions on just what is represented. One of the conclusions of the IEEE Task Force on Generating Unit Data Pooling (of the Application of Probability Methods Subcommittee) is that one must always focus on the planned use of the pooled data in developing the survey forms. The design of the IEEE survey was guided by the goals outlined in the Introduction.

From the members of the MAIN Transmission Outage Task Force, we are pleased to hear that our efforts in developing an effective survey have stimulated review and improvement in data collection procedures. This discusser underscores a important observation: pooling transmission outage data over all of North America provides a poor basis for the predicting the performance of any specific line where weather, terrain and other characteristics are known. Such data pooling over such a broad geographic area does, however, provide initial estimates, which are then tempered in accordance with local conditions. This is especially the case for rare events such as three-phase faults at 500kV and 765kV.

The Data Analysis Task Force agrees that it is desirable to establish a guideline for the collection of outage data on transmission of voltages below 230kV (69, 115, 135 and 161kV). We would recommend that the present questionnaire serve as a starting point for a collection system for outage history at these (sub)transmission voltages.

The DATF agrees with Mr. Ringlee in his observation that a high proportion of outages (both single and multiple) are terminal related. Because of earlier-discussed data deficiencies, many terminal-related outages were not included in the summaries, while line-related outages on the same lines were included. As a result, an even higher proportion of the outages are terminal related. We agree that this observation points to improved station equipment performance as a potentially fruitful area for improving the reliability of the transmission system.

Although it would be desirable to see how the performance of particular lines may have changed from the 1965 to 1985 surveys, the data collected in the 1965 survey are lost. The comparison of circuits of different designs within the 1985 survey, but operating in similar geographic areas, is difficult because of a lack of detailed geographic information requested on the lines. This is a comparison that can, however, be made using the general regional characteristics of the host utility, and will be considered in the next phase of this work.

A clarification on our procedure for removing certain outage data is necessary to address Mr. Gunderson's concern that such omissions may lead to outage rates which are significantly lower than the actual outage rates of the lines. In all cases, the exposure data were adjusted to avoid this consequence. Both line-related and terminal-related outages had to be removed. The largest block of data removed were terminal related outages as noted in Footnote No. 4 to Table 18. The reader is cautioned not to take the ratio of terminal-related to line-related outages, since the terminal-related outages are under represented.

Mr. Gunderson suggests that terminal-related outages on a circuit may not be linearly related to the number of terminals that line has as we have assumed. The reason cited is that the complexity of protection systems increases as the number of terminals increases. Table 18 indicates that a significant portion of the terminal-related outages are due to problems with the protective system at all voltages but 765kV. At 765kV, 100% of the circuits upon which outages were reported have only two-terminals [6]. We will delve more deeply into this observation in the next phase of our work. We cannot, however, do the same for variations in bus configuration, since we did not collect data to characterize this undoubtedly important variable. We agree with Mr. Gunderson that the nature of land development and weather characteristics along the r.o.w. might correlate with outage rate. There is always the balance to be struck, however, between what data might be desirable, what data is readily available, and the possible risk of overwhelming the person assembling and submitting the data.

We agree with Messrs. Endrenyi and Wang in their observation that the weather-related outages reported in Table 18 (under the "Environment" general cause) tell us little about the impact of weather. This is because we did not ask for a characterization of weather exposure in the circuit population data. Table 18 only confirms our suspicion that weather effects are the predominant outage cause within the "Environment" category.

We expect to make better use of the lightning-related outage data in the next phase of the data analysis. Lightning

performance will be correlated with isokeraunic level, and with number and angle of shielding wires. We may also find correlation of lightning outages with other design characteristics.

Ms. Volpe and Mr. Silverstein identify the Working Group on Performance Records as a supportive setting for further analysis of the data. The DATF will explore the merits of this suggestion.

It has been the intent of the Working Group on Statistics of Line Outages to document thoroughly the data collection system used in the 1985 survey and to identify its weaknesses [4,6]. The goal is to state the lessons learned and possibly to ease the preparations for the next general survey. In doing so, we would hope also to facilitate the capture and observation of trends over time as Ms. Volpe and Mr. Silverstein have suggested.

Mr. Rashkes has provided some provocative observations on the practice and performance of the Russian transmission system operating at voltages similar to those that we have surveyed. Of particular interest to the DATF are the observations on the fraction of single-phase faults that have occurred on the Russian system, and on the benefits of single-pole reclosing. From Table 21 of the paper, we similarly observe that single-phase faults caused by line-related problems are the predominant cause of outage at all voltages. Whereas the Russian experience has indicated that 60% to 98% of the total trippings are from single-phase faults, our data from Table 21 indicate this portion to lie in the range from 18% to 52%. Perhaps, without single-pole switching to help indicate the nature of the fault, there is a less accurate identification of the fault type. Mr. Rashkes summarizes the success of single- and three-phase high-speed reclosing as lying in the range of a half to three-quarters. If we were to assume the "success" rate to be defined as the ratio of momentary line-related outages to the sum of momentary and sustained line-related outages, we observe a success rate in the range from a third to two-thirds. Single-pole reclosing may have a significant and important positive impact on transmission network reliability.

Some interesting comparisons may also be made to Mr. Rashkes' summary of outage causes. Wind and contamination have much less impact in our survey, which may be the result of either differences in design, or differences in operating environment. Lightning, on the other hand, has a greater impact on line outages. This may be due to a basic difference in circuit design, or to a greater incidence of lightning near those circuits on which data were reported?

We observe that the Russian data appears to be normalized only by circuit length, and not by the number of terminals involved. It appears that no distinction was made between terminal- and line-related outages.

The utilities and power pools responded to the IEEE survey of overhead transmission outages with the agreement that the "data will be held in strict confidence and only summaries will be reported..." The Working Group is, therefore, obliged not to release the detailed data for use by others. As an alternative we are willing to work with any other IEEE working group or task force in exploring the implications of the data. This would include Mr. McDermott's suggestion that we discuss possible data analysis that may be of interest to the IEEE Working Group on Estimating the Lightning Performances of Transmission Lines.

The DATF thanks Mr. Oprisan for sharing his insight on the benefits of pooling data. Since he has offered a sampling of the CEA transmission statistics, we will make a few comparisons of the results at 230kV. (The reader will recall that our data includes CEA data.) Referring to our Table 18 and converting miles to kilometers, our data indicates a line-related sustained forced outage frequency of 0.80 per 100 km.a (compared to CEA's 0.54 per 100 km.a), and momentary forced outage frequency of 0.44 per 100 km.a (compared to CEA's 0.58 per 100 km.a). Our Table 22 shows an average duration of the line-related sustained forced outages of 7.9 hours (compared to CEA's 12.4 hours). With regard to terminal-related sustained forced outages, our data indicates a frequency of 0.06 per terminal.a (compared to CEA's 0.14 per terminal.a), and a duration of 9.8 hours (compared to CEA's 4.7 hours).

Mr. Oprisan has identified a point of confusion in our definition of momentary and sustained outages. We define a momentary outage as one whose duration is one minute or less. Since we request outage start and end times only to the nearest minute, the next larger increment in duration is two minutes. Thus any outage with calculated duration of two minutes or more is considered sustained. Depending on how the data submitter may have rounded off the outage start and end times, an outage that was in fact of duration between one and two minutes may be classified momentary or sustained.

Mr. Oprisan observes that the failure of terminal equipment is listed as outage causes of circuits. Our approach treats the a transmission line and its terminal equipment as a unit, and provides statistics on the "transmission unit." An alternate approach is oriented to the development of statistics on the transmission components. The latter approach is favored by CEA. The DATF found that there are some problems with converting data collected under one approach to a form compatible with the other approach.

Again we thank the discussers for their questions, comments and recommendations. These have provided us with the impetus to forge onward with a more detailed analysis of the data collected.

Manuscript received April 13, 1993.

FREQUENCY OF TRANSMISSION LINE OUTAGES IN CANADA

Don O. Koval
Dept. of Electrical Engineering
University of Alberta
Edmonton, Alberta
T6G 2G7 Canada

Abstract - Frequent transient and sustained forced outages of transmission equipment can significantly affect the performance of industrial and commercial power systems and the processes they control. A knowledge of the primary causes (e.g., adverse weather, defective equipment, etc.) of transmission line sustained and transient forced outages and which physical components of a transmission line (e.g., line conductors, structure, hardware, etc.) are affected is essential for designing and maintaining reliable transmission systems. Historical transmission reliability data provides the ability to predict [1] the performance of various transmission line configurations and assess the impact of forced outages on industrial and commercial power systems. When no historical voltage sag data is available, historical transmission line reliability statistics can be used to predict the voltage sag activities at a particular site. The prediction methodology will appear in the next edition of IEEE Std. 493 (i.e., IEEE Gold Book). This paper will present a summary of the Canadian Electrical Association's Equipment Reliability Information System statistics on the forced outage performance characteristics of transmission equipment for Canadian utilities for the period 1988 - 1992. The paper will reveal the structure of the data base and present relevant summary data necessary for the application of these reliability methodologies[1].

I. INTRODUCTION

"In 1975 the Canadian Electrical Association (CEA) adopted a proposal to create a facility for centralized collection, processing and reporting of reliability and outage statistics for electrical generation, transmission and distribution equipment. To coordinate the development of this Equipment Reliability Information System CEA constituted the Consultative Committee on Outage Statistics. In 1978, the transmission stage of the information system was implemented when Canadian utilities began supplying data on transmission equipment in accordance with the Instruction Manual for Reporting Component Forced Outages of Transmission Equipment" [2].

The performance of transmission lines can be viewed from many different perspectives. To understand the variance in these perspectives, it is necessary to define the data base structure of transmission line performance data. The structure for the CEA transmission equipment forced outage data base is shown in Figure 1.

The major classifications of transmission lines are according to their operating voltage level and their supporting structure (e.g., double pole wood construction). The forced outage data is divided into two categories; namely, sustained and transient forced outages. The sustained forced outages are further divided into "line-related" and "terminal related" forced outages while transient forced outages are only defined in terms of "line-related" forced outages. The "line-related" and "terminal related" forced outages are further subdivided into primary causes and subcomponent categories.

The identified ***primary causes*** of transmission line forced outages are:

- defective component
- adverse weather
- adverse environment
- system condition
- human element
- foreign interference
- unknown

The identified ***subcomponents*** affected by transmission line forced outages are:

- structural
- joints & deadends
- conductor
- insulation system
- ground wire
- hardware
- other

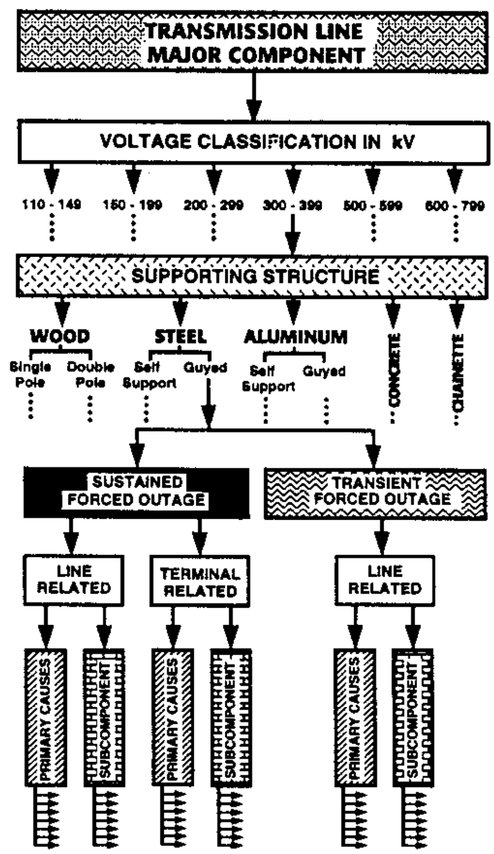


Fig. 1 Canadian Electrical Association transmission line data base structure

Historical transmission line forced outage statistics provide key answers to often posed questions:

1. What are the prime causes of transmission line forced outages?
2. Does the frequency of transmission line forced outages vary significantly with the supporting structure (e.g., wood, steel etc.) and the operating voltage of a transmission line?
3. How long are transmission line sustained forced outages?
4. What is the weakest link of a transmission line? Is it the line conductors, line hardware, insulators, ground wires, its structure?

Table I below is a summary of the inventory at December 31, 1992 by voltage classification based on the data supplied by all utility contributors.

TABLE I
INVENTORY OF TRANSMISSION LINES
AS OF DECEMBER 31, 1992

	VOLTAGE CLASS					
STATISTIC	110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
Length (km.)	41,456	12,255	37,096	9,857	9,061	10,191
Terminals	2,057	167	1,125	271	221	331

II TRANSMISSION LINE "LINE-RELATED" SUSTAINED FORCED OUTAGES

"A **sustained forced outage** refers to a transmission line-related forced outage, the duration of which is one minute or more. It does, therefore, not include automatic reclosing events" [2]. The percentage of transmission line "line-related' sustained forced outages stratified according to the primary cause of forced outages and voltage classification is shown in Figure 2. A summary of transmission line statistics for line-related sustained forced outages is shown in Table II.

The identification of the primary cause as adverse weather (i.e., lightning, rain, freezing rain, ice, snow, wind, high ambient temperature, low ambient temperature, freezing fog or frost, tornadoes) versus defective equipment requires some clarification[3]. "If it is known that equipment has failed as a consequence of adverse weather and that the weather conditions were within the design parameters of the failed equipment then the PRIMARY CAUSE CODE must be DEFECTIVE EQUIPMENT. And conversely, if the weather conditions were outside of the design parameters of the failed equipment (e.g., tornado) the PRIMARY CAUSE CODE must be ADVERSE WEATHER.

TABLE II
SUMMARY OF TRANSMISSION LINE STATISTICS FOR
LINE-RELATED **SUSTAINED** FORCED OUTAGES

	VOLTAGE CLASS					
STATISTIC	110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
Kilometer Years (km.a)	215,547	10,867	180,449	46,169	42,431	50,998
Number of Outages	2,849	73	992	133	263	91
Total Time (h)	22,231	619	12,171	2,799	6,291	557
Frequency per 100 km.a	1.3218	0.6718	0.5497	0.2881	0.6198	0.1784
Mean Duration (h)	7.8	8.5	12.3	21.0	23.9	6.1

For all voltage classes of transmission lines, **adverse weather** accounts for approximately 70% of sustained forced outages with the exception of the 600-799 kV voltage class. For the 600-799 kV voltage class, **adverse environment** accounts for a significant percentage of sustained transmission line outages (e.g., 32.96%).

Defective equipment and foreign interference account for another approximately 20 percent of the sustained forced outages while the remaining primary cause categories account for approximately 10% of the sustained forced outages. Adverse environment includes the following conditions: salt spray, industrial pollution, humidity, corrosion, vibration, fire and flooding. [3]

The frequency of transmission line "line-related" sustained forced outages classified by voltage class and supporting structure expressed in "outages per 100 km per year" is listed in Table III.

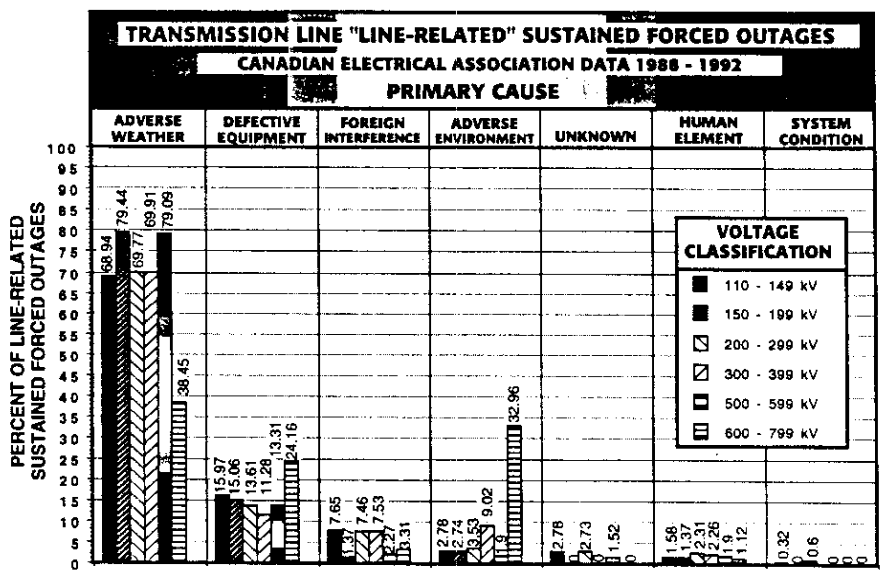


Fig. 2 Percent of transmission line "line-related" sustained forced outages stratified by primary cause and voltage class

TABLE III
FREQUENCY OF LINE-RELATED SUSTAINED FORCED OUTAGES CLASSIFIED BY VOLTAGE CLASS AND SUPPORTING STRUCTURE EXPRESSED IN "outages per 100 km per year"

SUPPORTING STRUCTURE	VOLTAGE CLASS 110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
WOOD SINGLE POLE	0.9725	-	-	-	-	-
WOOD DOUBLE POLE	1.0543	0.8589	0.6147	0.0974	-	-
STEEL SELF-SUPPORTING	1.8976	0.3515	0.4565	0.3114	0.5765	0.2442
STEEL GUYED	1.8722	-	1.6193	0.2243	0.8399	0.0822
ALUMINUM SELF-SUPPORTING	1.3793	-	0.9205	-	0.5253	-
ALUMINUM GUYED	-	-	0.3727	-	-	-
CHAINETTE	-	-	-	-	-	0.1998
ALL SUPPORTING STRUCTURES	1.3218	0.6718	0.5497	0.2881	0.6198	0.1794

The frequency of transmission line outages is the number of outages divided by kilometer years which are in turn divided by 100. It is interesting to note the variance in the frequency of sustained forced outages with increasing voltage classes for a given support structure. The primary causes of sustained forced outages for each supporting structure tend to follow the distinctive statistical pattern shown in Figure 2. Detailed information on individual structures is presented in Reference 2.

The percentage of sustained transmission line line-related forced outages stratified according to the subcomponent which caused a forced outage is shown in Figure 3. The highest percentage of line-related sustained forced outages for all voltage classes is the "insulation system" subcomponent of a transmission line. It is important to note: the "insulation system (of a transmission line) includes the insulation by the atmosphere and/or by the insulators. Hardware is intended to comprise accessories associated with the line conductors but not with the ground wires" [3].

III DURATION OF TRANSMISSION LINE LINE-RELATED SUSTAINED FORCED OUTAGES BY VOLTAGE CLASSIFICATION AND SUPPORTING STRUCTURE

The mean and median duration of line-related sustained transmission line forced outages classified by supporting structure and voltage class are listed in Table IV. Note the significant differences in the mean duration of sustained forced outages for a given supporting structure and for a given voltage class. The important point to not from Table IV is the significant variance between the mean and median line-related sustained forced outage duration levels. The mean value is particularly sensitive to lengthy forced outages which results in the mean value being significantly greater than the median value.

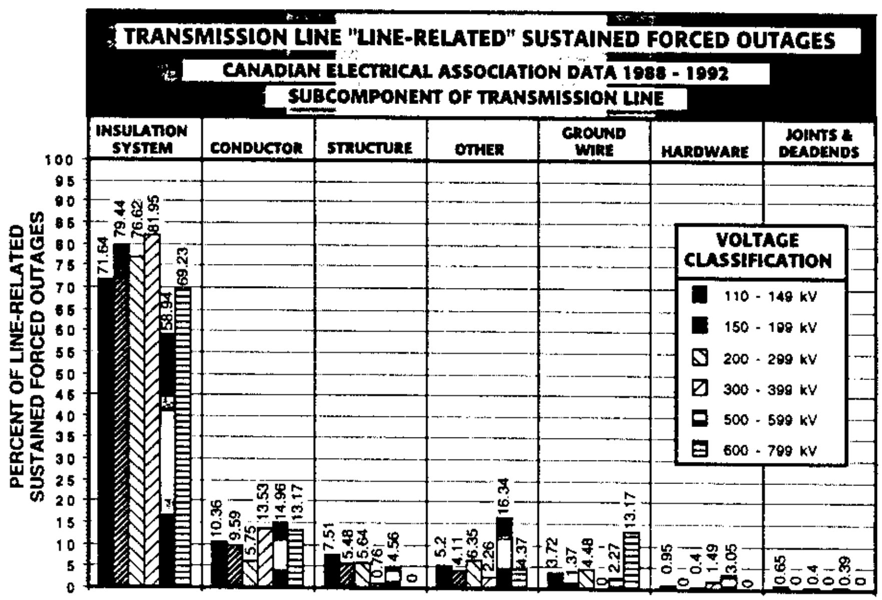


Fig. 3 Percent of transmission line "line-related" sustained forced outages stratified by subcomponent and voltage class

TABLE IV
THE MEAN AND MEDIAN DURATION OF LINE-RELATED **SUSTAINED** FORCED OUTAGES CLASSIFIED BY VOLTAGE CLASS AND SUPPORTING STRUCTURE EXPRESSED IN HOURS

SUPPORTING STRUCTURE	VOLTAGE CLASS 110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
WOOD SINGLE POLE	10.8 (0.31)	-	-	-	-	-
WOOD DOUBLE POLE	9.4 (0.10)	4.0 (0.22)	9.8 (0.12)	-	-	-
STEEL SELF-SUPPORTING	6.1 (0.08)	27.2 (0.16)	11.7 (0.15)	22.4 (0.21)	14.5 (0.10)	6.3 (0.05)
STEEL GUYED	1.1 (0.05)	-	19.1 (0.17)	1.1 (0.21)	42.4 (0.22)	1.9 (0.15)
ALUMINUM SELF-SUPPORTING	8.7 (2.26)	-	43.7 (0.05)	-	64.9 (0.79)	-
ALUMINUM GUYED	-	-	7.4 (1.13)	-	-	-
CHAINETTE	-	-	-	-	-	9.0 (0.24)
ALL SUPPORTING STRUCTURES	7.8 (0.10)	8.5 (0.22)	1 2.3 (0.15)	21.0 (0.20)	23.9 (0.15)	6.1 (0.08)

NOTE: Values not enclosed in brackets represent the average value while those values enclosed in brackets represent the median duration of sustained forced outages.

IV TRANSMISSION LINE "LINE-RELATED" TRANSIENT FORCED OUTAGES

A "transient forced outage refers to a transmission line forced outage the duration of which is less than one minute and is, therefore, recorded as zero. It covers only automatic recloser events". The actual duration of transmission line transient forced outages can be estimated from power line monitors but the process is prohibitively expensive and problematic since the duration of the transient forced outage is dependent upon the location of the power line monitor with respect to the origins of the transient forced outage. The percentage of transmission line line-related transient forced outages stratified according to the primary cause of forced outages and voltage classification is shown in Figure 4. A summary of transmission line statistics for line-related transient forced outages is shown in Table V.

TABLE V
SUMMARY OF TRANSMISSION LINE STATISTICS FOR LINE-RELATED **TRANSIENT** FORCED OUTAGES

STATISTIC	VOLTAGE CLASS 110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
Kilometer Years (km.a)	215,547	10,867	180,449	46,169	42,431	50,998
Number of Outages	2,493	12	1,031	31	904	35
Frequency per 100 km.a	1.1566	0.1104	0.5714	0.0671	2.1305	0.0686

The percentage of transmission line "line-related" transient forced outages stratified by subcomponent and voltage class is shown in Figure 5. Similar to sustained forced outages, the insulation system of a transmission line accounts for approximately 90% of all transient forced outages for all transmission line voltage classes. Transmission line conductor and ground wire subcomponents represent a very small percent of the sustained forced outages.

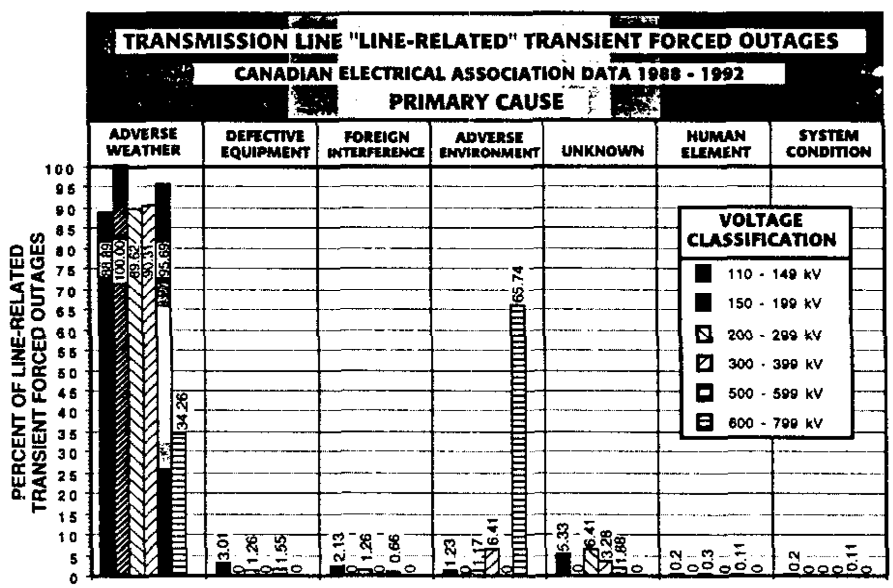


Fig. 4 Percent of transmission line "line-related" transient forced outages stratified by primary cause and voltage class

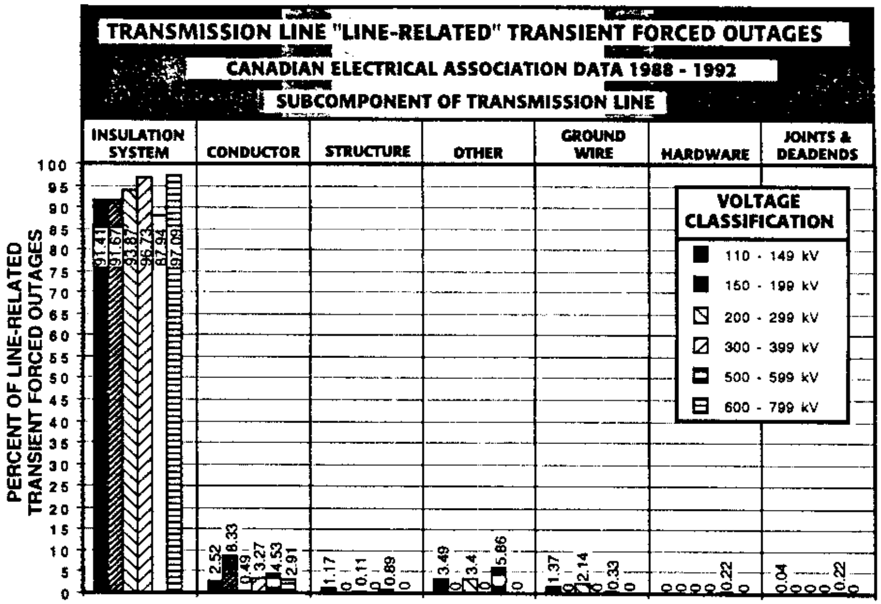


Fig. 5 Percent of transmission line "line-related" transient forced outages stratified by subcomponent and voltage class

The major primary cause of transient forced outages is "adverse weather which accounts for approximately 90 percent of all transient forced outages for all voltage classes except the 600-799 kV class where adverse weather is the dominant cause. The statistical pattern of primary causes of transient forced outages and sustained forced outages is similar.

The frequency of transmission line transient "line-related" forced outages classified by voltage class and supporting structure expressed in "outages per 100 km per year" is listed in Table VI. The frequency of transient forced outages varies significantly for a given supporting structure and for a given voltage class similar to Table III for sustained forced outages. Figure 6 reveals the frequency of transient and sustained forced outages for various voltage classes.

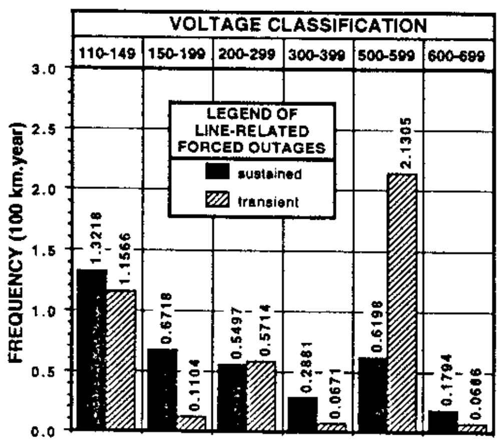


Fig. 6 Frequency of line-related sustained and transient forced outages of transmission lines by voltage classification

TABLE VI
FREQUENCY OF LINE-RELATED TRANSIENT FORCED OUTAGES CLASSIFIED BY
VOLTAGE CLASS AND SUPPORTING STRUCTURE
EXPRESSED IN "outages per 100 km per year"

SUPPORTING STRUCTURE	VOLTAGE CLASS 110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
WOOD SINGLE POLE	1.2619	-	-	-	-	-
WOOD DOUBLE POLE	1.0495	0.1456	0.7073	0.0	-	-
STEEL SELF-SUPPORTING	1.2743	0.0502	0.5259	0.0764	2.0363	0.1390
STEEL GUYED	0.4309	-	0.2816	0.0408	2.8263	0.0110
ALUMINUM SELF-SUPPORTING	-	-	0.8368	-	1.3133	-
ALUMINUM GUYED	4.2912	-	-	-	-	-
CONCRETE	4.6875	-	-	-	-	-
ALL SUPPORTING STRUCTURES	1.1566	0.1104	0.5714	0.0671	2.1305	0.0686

V TRANSMISSION LINE "TERMINAL-RELATED" FORCED OUTAGES

A summary of transmission line statistics for terminal-related sustained forced outages is shown in Table VII. It is important to note in Table VII the significant difference between the mean and median duration of terminal-related sustained force outages revealing the impact of lengthy outage duration levels on the mean value.

TABLE VII
SUMMARY OF TRANSMISSION LINE STATISTICS FOR TERMINAL-RELATED SUSTAINED FORCED OUTAGES

STATISTIC	VOLTAGE CLASS 110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
Kilometer Years (km.a)	9,583	627	5,263	1,147	606	539
Number of Outages	1,574	82	991	150	186	153
Total Time (h)	16,352	619	8,618	3,889	8,887	3,949
Frequency per 100 km.a	0.1642	0.1307	0.1883	0.1307	0.3069	0.2394
Mean Duration (h)	10.4	7.0	8.7	25.9	47.8	25.8
Median Duration (h)	0.05	0.30	0.22	0.37	0.64	1.70

The percent of transmission line "terminal-related" forced outages classified by their primary cause and voltage level is shown in Figure 7. Note that the statistical outage patterns of the primary causes of "terminal-related" forced outages is significantly different than "line-related" sustained and transient forced outages. Defective equipment for all voltage classes is the dominant cause of "terminal-related" forced outages. Damage equipment includes some of the following categories [2]:

- deterioration due to age
- incorrect manufacturing design
- incorrect manufacturing materials
- incorrect manufacturing assembly
- lack of maintenance

Research is required to investigate why defective equipment is the dominant cause for transmission terminal-related forced outages for all voltage categories and can the impact of equipment failures be reduced economically. Some of the following questions could be posed:

(1) Are the equipment reliability design levels too low and what are these levels set by the manufacture and utilities?

(2) Is the equipment subjected to rigorous compliance testing during commissioning prior to being accepted?

(3) Is the equipment maintained adequately?

(4) Is the equipment installed correctly in the field?

The "human element" is the second most dominant causes of forced outages while adverse weather is significantly less for all voltage classes with the exception of the 150-199 kV voltage class. The category "human element" includes some of the following issues[2]:

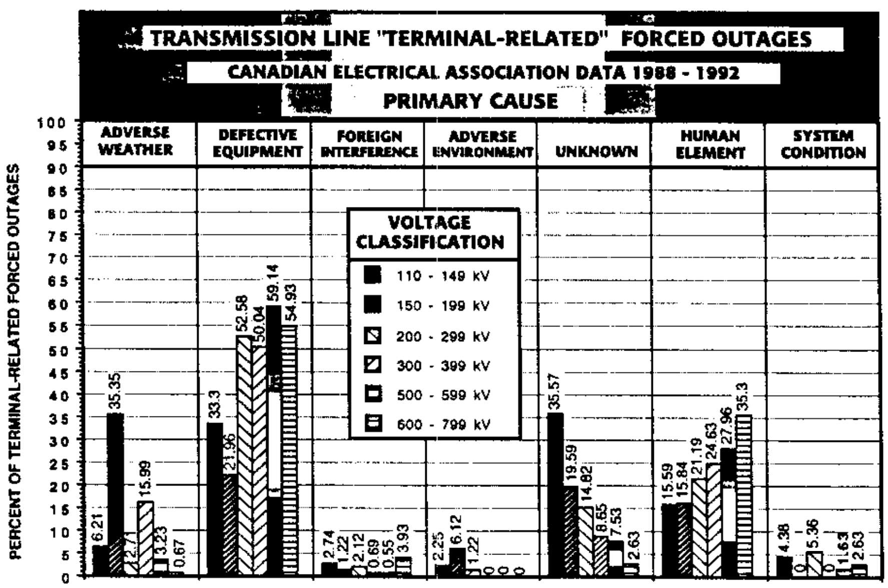


Fig. 7 Percent of transmission line "terminal-related" sustained forced outages stratified by primary cause and voltage class

- incorrect system records or diagrams
- incorrect use of equipment
- incorrect construction, installation or maintenance
- incorrect protection setting
- switching error
- testing
- incorrect circuit labelling
- deliberate or accidental damage by employees or utility contractors

Research is required to define why the human element is a significant primary cause. Questions concerning the adequacy of training and adaptation to new technologies can be posed.

The percent of transmission line "terminal-related" forced outages classified by their voltage class and subcomponents is shown in Figure 8. With reference to Figure 8, "control and protection equipment" account for the largest percent of known sustained forced outages for all voltage classes. Several questions can be posed on the dominance of "control and protection equipment" causing terminal-related forced outages. They are:

(1) Is the "new" technology a problem"?

(2) Are the setting too complex resulting in conflicting protection control decisions and subsequent failures?

(3) Is the control and protection equipment rigorously tested prior to installation and maintained adequately during its service life?

The "unknown" category was the largest factor for the lower voltage categories and significantly less at the upper voltage levels. For the 600-699 kV voltage class, the disconnect subcomponent was a significant factor. The disconnect and potential device subcomponents accounted for approximately 10 to 30 percent of terminal-related forced outages.

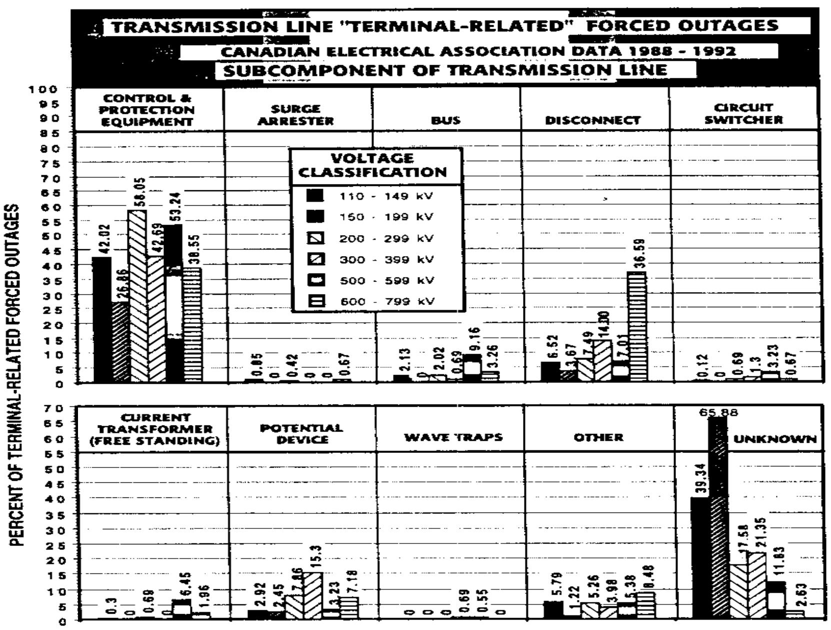


Fig. 8 Percent of transmission line "terminal-related" sustained forced outages stratified by subcomponent and voltage class

VI CONCLUSIONS

This paper has present a summary of the Canadian Electrical Association's transmission equipment statistics in graphical form to reveal the line-related and terminal-related forced outage performance characteristics of transmission lines. Detailed statistics on other major component of the transmission equipment (i.e., cable, transformer bank, circuit breaker, synchronous compensator, static compensator, shunt reactor bank, shunt capacitor bank and series capacitor bank) are beyond the scope of this paper but are contained in Reference 3.

The frequency and duration of transmission line forced outages classified by their supporting structures was presented to reveal the variance in the performance of different supporting structures (e.g., wood, steel, etc.) for various voltage levels and the possible variance in using a single index for a specific voltage class. The paper revealed the significant difference between the mean duration of transmission line forced outages and the median revealing the impact of lengthy transmission line outages on the mean value. For all voltage classifications, fifty percent of the time the duration of sustained forced outages was less than 15 minutes.

The primary cause of transmission line sustained forced outages was "adverse weather" and accounted for approximately 70% of the sustained forced outages. The insulation system subcomponent accounted for the largest percentage of sustained forced outages. These results provide the research base necessary to improve transmission line design characteristics. The primary cause and major subcomponent that resulted in transient forced outages were similar to the sustained forced outage characteristics (i.e., approximately 90% of the transient forced outages were caused by "adverse weather" and were attributed to the "insulation system".

The primary cause of transmission line "terminal-related" forced outages was "defective equipment" followed by "human element". The "control and protection equipment" accounted for the highest percentage of terminal-related forced outages.

These findings provide a knowledge base which is essential to analyse and evaluate the performance of transmission line with the objective of maximizing their reliability performance. For example, as transmission lines age how will these statistics change and at what point in time and at what level of performance degradation will it be necessary to replace these facilities?

A question often posed is: ' how good are those old transmission line surveys? Answer: they are pretty good, don't throw them away, they are required for trending analysis. The 1988-92 survey results were compared with the 1978-83 survey results for line-related and terminal-related forced outages. The same forced outage patterns were dominate in both surveys. A simple comparison is shown in Table VIII where it is clear that the variance is small for terminal-related forced outages while line-related forced outages the variance is significantly larger (i.e., note lower levels in the latest survey).

TABLE VIII
SUMMARY OF 1988-92 AND 1978-83 FREQUENCY OF LINE-RELATED AND TERMINAL RELATED FORCED OUTAGES

	VOLTAGE CLASS					
STATISTIC	110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
Frequency of line-related forced outages (per 100 km year)						
(1998-92)	1.3218	0.6718	0.5497	0.2881	0.6198	0.1784
(1978-83)	2.4942	NA	0.9096	0.4444	1.0036	0.3551
Frequency of terminal-related forced outages (per 100 km year)						
(1998-92)	0.1642	0.1307	0.1883	0.1307	0.3069	0.2394
(1978-83)	0.1715	NA	0.2274	0.1596	0.2275	0.4895

VII ACKNOWLEDGEMENTS

The author would like to thank the following members of the Canadian Electrical Association: Morel Oprisan, Edward M. Ezer and Raymond A. Del Bianco for their invaluable discussions and assistance in providing me with the CEA Equipment Reliability Information System reports on "Forced Outage Performance of Transmission Equipment and the Instruction Manuals for Reporting.

VII REFERENCES

1. Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems, IEEE Std. 493, (IEEE Gold Book).

2. Instruction Manual For Reporting Component Forced Outages of Transmission Equipment, Canadian Electrical Association, Suite 1600, One Westmount Square, Montreal, Quebec, H3Z 2P9.

3. Report: Forced Outage Performance of Transmission Equipment for the Period January 1, 1988 to December 31, 1992, Canadian Electrical Association, Suite 1600, One Westmount Square, Montreal, Quebec, H3Z 2P9.

4. An IEEE Survey on U.S. and Canadian Overhead Transmission Outages at 250kV and Above, Data Analysis Task Force, Working Group on Statistics of Line Outages, General Systems Subcommittee, Transmission & Distribution committee, IEEE Transactions on Power Delivery, vol. 9, No. 1, January 1994, pp. 21-39.

5. IEEE Task Force on Line Design Characteristics, Working group on statistics of Line Outages, "An IEEE Survey of Transmission Line Population and Design Characteristics:, IEEE Transactions on Power Delivery, Vol. 6, pp. 1934-45, October, 1991.

6. IEEE Standard Terms for Reporting and Analyzing Outage Occurrences and Outage States of Electrical Transmission Facilities, IEEE Std. 859-1987.

7. IEEE Task Force on the Requirements for the Survey of Line Outage Data, "IEEE AT&D Working Group on Statistics of Line Outages:Background, Status and Prospects:, Proceeding of the 14th INTER-RAM Conference for the Electric Power Industry, Toronto, Ontario, pp. 255-262, May 26-29, 1987.

8. Baribeau, M.A., Driscoll, C.T. and McGillis, D. "The Canadian Electrical Association's Equipment Reliability Information System", Proceedings of the Third International Conference on Reliability of Power Supply Systems, IEC conference Publication No. 225, September 19-21, 1983, London, UK, pp. 150-154.

9. Baribeau, M.A., McGillis, D., "Analysis of Transmission Equipment Performance Based on the CEA System", Canadian Society for Electrical Engineering, May, 1984 Conference, Halifax, Nova Scotia.

10. "Predicting Transmission Outages for System Reliability Evaluations", Electric Power Research Institute, EPRI-3880, Project 1468-2, May, 1985,

11. Lauby, M.G., Khu, K.T., Polesky, R.W., Vandello, R.E., Doudna, J.H., Lehlman, P.J., Elempel, D.D., "MAPP Bulk Transmission Outage Data and Collection", Transactions on Power Apparatus and Systems, Vol., PAS-103, Jan. 1984, pp. 213-221.

12. Lauby, M.G., Ludorf, R.P., Doudna, J.H., Klempel, D.D., Lehman, P.J., Dahl, C.G., "Analysis of Pooling 345kV Bulk Transmission Outage Data Between the Mid-Continent Area Power Pool and Northeast Utilities, Trans, Transactions on Power Apparatus and Systems, Vol., PAS-104, Sept. 1985, pp. 2427-2434.

13. Lauby, M.G.,Doudna, J.H., Polesky, r.w., Lehman, P.J., Klempel, D.D., "Effects of Pooling Weather Associated MAPP ABulk Transmission Outage Data on Calculated Forced Outage Rates", Transactions on Power Apparatus and Systems, Vol., PAS-103, Aug. 1984, pp.2345-2351.

14. Patton, A.D., "Determination and Analysis of Data for Reliability Studies", IEEE Transactions of Power Apparatus and Systems, Vol. PAS-87, Jan. 1968., pp. 84-100.

15. Ringlee, R.J., "Techniques for Pooling Outage Data", Pennsylvania Electric Association (PEA), System Planning Committee Fall Meeting, Sharon, P.A., October, 1967.

Transmission Equipment Reliability Data from Canadian Electrical Association

Don O. Koval, *Fellow, IEEE*

Abstract—Frequent forced outages of transmission equipment can significantly affect the performance of industrial and commercial power systems and the processes they control. Historical transmission reliability data provides the ability to predict the performance of various transmission line configurations and assess the economic impact of forced outages on industrial and commercial power systems. The prediction methodologies are presented in IEEE Std. 493 (i.e., IEEE Gold Book) [1]. This paper will present a summary of the Canadian Electrical Association's Equipment Reliability Information System [2], [3] statistics on the forced outage performance characteristics of transmission equipment (i.e., transformers, circuit breakers, cables, etc.) for Canadian utilities for the period 1988-1992. The paper will reveal the structure of the data base and present relevant summary data (i.e., the frequency and duration of forced outages) necessary for the application of these reliability methodologies. A knowledge of the primary causes of the major equipment forced outages as to whether the outages are primarily due to the subcomponents of the major equipment or to its terminal equipment is essential for designing, operating and maintaining a reliable transmission system. This paper will discuss and identify for each major equipment the primary subcomponent (e.g., transformer windings) and the terminal equipment (e.g., auxiliary equipment) which dominated the forced outage statistics of the major equipment for the five year period.

Index Terms—Transmission, equipment, reliability, CEA, failure.

I. Introduction

"In 1975, the Canadian Electrical Association (CEA) adopted a proposal to create a facility for centralized collection, processing and reporting of reliability and outage statistics for electrical generation, transmission and distribution equipment. To coordinate the development of this Equipment Reliability Information System CEA constituted the Consultative Committee on Outage Statistics. In 1978, the transmission stage of the information system was implemented when Canadian utilities began supplying data on transmission equipment in accordance with the Instruction Manual for Reporting Component Forced Outages of Transmission Equipment" [2].

The performance of transmission lines can be viewed from many different perspectives. To understand the variance in these perspectives, it is necessary to define the data base structure of transmission line performance data. The structure for the CEA transmission equipment forced outage data base is illustrated in Fig. 1.

With reference to Fig. 1, the frequency and duration of major equipment forced outages for each major component presented in this paper will be stratified by voltage classification which will further be divided into two categories, namely;

1) All integral subcomponents of the major equipment
2) All terminal equipment of the major equipment.

For each major component, the dominant subcomponent(s) (e.g., on-load tap changer) and dominant major equipment terminal failures (e.g., control and protection equipment) will be presented. A presentation of all the other subcomponent and terminal equipment failure statistics is beyond the scope of this paper but can be obtain in [3]. Two reliability indices are presented for the duration of equipment forced outages, namely, the mean and mediam. For the majority of transmission system equipment forced outages, there is a significant difference between the mean and the mediam indicating the skewness of the underlying distributions and the sensitivity of the mean to lengthy outages. Given the frequency and duration of forced transmission equipment outage statistics, the reliability methodologies presented in IEEE Std. 493 (i.e., IEEE Gold Book) can be used to predict the performance of transmission system operating configurations and assess their impact on industrial and commercial facilities.

Historical transmission system equipment forced outage statistics provide key answers to often posed questions:

1) What are the prime causes of transmission system equipment forced outages?
2) Does the frequency of transmission system equipment forced outages vary significantly between its internal subcomponent and its associated terminal equipment?
3) How long are transmission system equipment forced outages?
4) What are the dominant subcomponent and terminal equipment outages which significantly degrade the performance of a major piece of transmission system equipment?

II. Transformer Banks

In the Canadian Electrical Association's (CEA) "Equipment Reliability Information System," two types of transformer banks are considered, namely "one three phase element" and "three single-phase elements." The subcomponents of these transformer bank is divided into the following components:

1) Bushing (Including CT's).

Paper ICPSD 95-15, approved by the Power Systems Engineering Committee of the IEEE Industry Applications Society for presentation at the 1995 Industrial & Commercial Power Systems Technical Conference, San Antonio, TX, May 7-11. Manuscript released for publication May 23, 1996.

The author is with the Department of Electrical Engineering, University of Alberta Edmonton, Alta., Canada T6G 2G7.

Publisher Item Identifier S 0093-9994(96)07224-6.

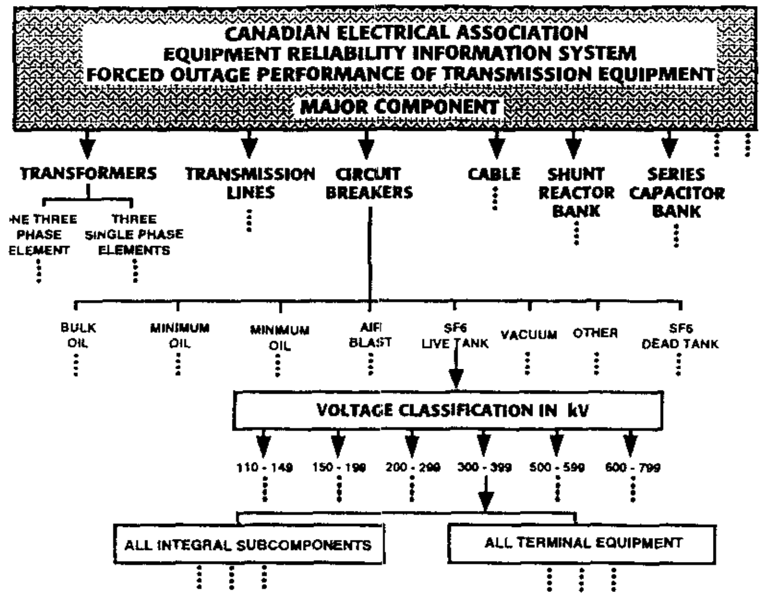


Fig. 1. Canadian Electrical Association transmission equipment data base structure.

2) Windings.
3) Core.
4) Leads.
5) Cooling Equipment.
6) Auxiliary Equipment.
7) Other.

The identified terminal equipment categories for transformers are:

1) Control and Protection Equipment.
2) Surge Arrester.
3) Bus.
4) Disconnect.
5) Circuit Switcher.
6) Current Transformer (Free Standing).
7) Potential Devices.
8) Motor-Operated Ground Switch.
9) Other.
10) Unknown.

The frequency and duration of all integral subcomponents and all terminal equipment forced outages for **one three phase element transformer banks** are listed in Table I.

The dominant known cause(s) of **subcomponent** forced outages for *single three phase transformer banks* for each voltage class and their percentage of the total frequency of subcomponent forced outages are:

110–149 kV	On-load Tap Changer	28.33%
150–199 kV	Auxiliary Equipment	44.40%
200–299 kV	On-load Tap Changer	33.13%
300–399 kV	On-load Tap Changer	25.00%
110–149 kV	On-load Tap Changer	21.10%
150–199 kV	Auxiliary Equipment	39.33%
200–299 kV	Cooling Equipment	15.91%
300–399 kV	On-load Tap Changer	26.32%
500–599 kV	Cooling Equipment	22.22%
600–799 kV	Windings	26.67%
	Bushings (including C.T.,'s)	20.00%
	Cooling Equipment	20.00%
110–149 kV	On-load Tap Changer	28.33%
500–599 kV	On-load Tap Changer	33.33%
	Windings	25.00%
600–799 kV	Cooling Equipment	26.51%

The dominant known cause(s) of **{terminal equipmen** forced outages for *single three phase transformer banks* fo each voltage class and their percentage of the total frequenc of terminal equipment forced outages are:

110–149 kV	Control & Protection Equipment	42.06%
150–199 kV	Control & Protection Equipment	75.00%
200–299 kV	Control & Protection Equipment	42.37%
300–399 kV	Control & Protection Equipment	55.55%
500–599 kV	Control & Protection Equipment	37.04%
600–799 kV	Control & Protection Equipment	50.00%

The frequency and duration of all integral subcomponent and all terminal equipment forced outages for **three single—phase element transformer banks** are listed in Tabl II.

The dominant known cause(s) of subcomponent force outages for *three single-phase transformer banks* for eac voltage class and their percentage of the total frequency o subcomponent forced outages are:

TABLE I
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES TRANSFORMER BANK ONE THREE PHASE ELEMENT (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
110 - 149 kV	0.0330	509.4	13.88	0.0936	28.0	3.85
150 - 199 kV	0.0510	1.3	0.72	0.0227	52.3	19.49
200 - 299 kV	0.0389	311.1	18.81	0.1136	35.7	5.98
300 - 399 kV	0.0291	745.6	15.13	0.0491	27.2	8.03
500 - 599 kV	0.0587	2,204.3	80.84	0.1320	11.0	4.47
600 - 799 kV	0.1058	1,458.7	8.42	0.0772	76.2	9.10

TABLE II
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES TRANSFORMER BANK THREE SINGLE PHASE ELEMENTS (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
110 - 149 kV	0.0372	173.2	13.72	0.0512	50.9	7.08
150 - 199 kV	0.1632	91.6	3.12	0.0715	47.5	1.67
200 - 299 kV	0.0422	62.2	5.43	0.0498	36.9	1.72
300 - 399 kV	0.0886	426.8	7.07	0.0466	46.9	2.60
500 - 599 kV	0.0327	146.4	15.48	0.0738	18.0	1.92
600 - 799 kV	0.0560	1,550.0	37.07	0.0485	1,157.1	8.05

TABLE III
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS110-149 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPT-ING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
BULK OIL	0.0311	165.8	14.87	0.0522	20.5	2.27
MINIMUM OIL	0.0216	466.0	24.94	0.0339	31.9	0.17
AIR BLAST	0.0402	171.7	21.38	0.0476	116.4	0.13
SF6 LIVE TANK	0.0251	93.0	4.94	0.0474	121.0	0.28
VACUUM	-	-	-	-	-	-
OTHER	-	-	-	-	-	-
SF6 DEAD TANK	0.2366	84.2	24.50	0.2340	72.7	8.69

The dominant known cause(s) of **terminal equipment** forced outages for *three single-phase transformer banks* for each voltage class and their percentage of the total frequency of terminal equipment forced outages are:

110-149 kV	Control & Protection Equipment	31.33%
150-199 kV	Control & Protection Equipment	41.16%
200-299 kV	Control & Protection Equipment	61.54%
300-399 kV	Control & Protection Equipment	60.00%
500-599 kV	Control & Protection Equipment	55.74%
600-799 kV	Control & Protection Equipment	46.15%

III. CIRCUIT BREAKERS

In the Canadian Electrical Association's (CEA) "Equipment Reliability Information System," the following types of circuit breakers are considered:

1) Bulk Oil.
2) Minimum Oil.
3) Air Blast.
4) SF6-Live Tank.
5) Vacuum.
6) Other.
7) SF6-Dead Tank.

TABLE IV
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS 150-199 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPT-ING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
BULK OIL	0.0760	41.8	1.38	0.0760	5.6	0.67
MINIMUM OIL	0.0295	107.9	9.90	0.0349	7.3	0.69
AIR BLAST	0.0284	83.5	13.82	0.0481	307.9	3.10
SF6 LIVE TANK	-	-	-	-	-	-
SF6 DEAD TANK	0.0289	45.2	50.71	0.0289	15.0	14.6

TABLE V
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS 200-299 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPT-ING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
BULK OIL	0.0561	228.2	5.53	0.1121	25.2	2.41
MINIMUM OIL	0.0582	265.8	8.00	0.0678	62.3	0.96
AIR BLAST	0.1056	99.2	6.95	0.1300	94.5	4.13
SF6 LIVE TANK	0.0172	42.5	4.50	0.0438	8.3	0.30
VACUUM	-	-	-	-	-	-
OTHER	0.0118	4,490.2	4,490.20	0.0235	10.31	0.27
SF6 DEAD TANK	0.0741	105.5	12.96	0.1209	19.4	4.00

The subcomponents of each type of circuit breaker are divided into the following components:

1) Bushing (Including C.T.'s).
2) Operating Mechanisms.
3) Interrupters.
4) Insulation System (Support Insulators).
5) Resistors or Grading Capacitors.
6) Interrupting Medium.
7) Auxiliary Equipment.
8) Other.

The identified terminal equipment categories for each type of circuit breaker are:

1) Control and Protection Equipment.
2) Surge Arrester.
3) Bus.
4) Disconnect.
5) Circuit Switcher.
6) Current Transformer (Free Standing).
7) Potential Devices.
8) Other.
9) Unknown.

The frequency and duration of all integral subcomponents and all terminal equipment forced outages of each type of circuit breaker for each voltage class are listed in Tables III-IX, respectively.

The dominant known cause(s) of **subcomponent equipment** forced outages for **110-149 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

Operating Mechanisms	42.74%
Auxiliary Equipment	18.45%

The dominant known cause(s) of **terminal equipment** forced outages for **110-149 kV circuit breakers** and the percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	60.59%

The dominant known cause(s) of **subcomponent equipment** forced outages for **{150-199 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

Bushings	20.00%
Auxiliary Equipment	18.45%

The dominant known cause(s) of **terminal equipment** forced outages for **150-199 kV circuit breakers** and the

TABLE VI

FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS 300-399 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPTING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
BULK OIL	0.1000	20.4	20.43	-	-	-
MINIMUM OIL	0.0116	429.7	28.25	0.0466	274.6	5.45
AIR BLAST	0.0845	189.3	34.60	0.0513	88.2	0.95
SF6 LIVE TANK	0.0132	119.5	119.48	0.0658	3.7	0.63
SF6 DEAD TANK	0.1141	265.0	21.45	0.0552	22.6	2.74

TABLE VII

FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS 500-599 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPTING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
BULK OIL	0.0500	715.9	715.87	-	-	-
MINIMUM OIL	-	-	-	-	-	-
AIR BLAST	0.0849	106.1	15.55	0.1297	65.4	4.81
SF6 LIVE TANK	-	-	-	0.6500	3.8	1.73
OTHER	-	-	-	0.2500	96.3	96.32
SF6 DEAD TANK	0.1002	121.4	3.55	0.2246	218.3	7.27

TABLE VIII

FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS 600-699 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPTING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
MINIMUM OIL	-	-	-	-	-	-
AIR BLAST	0.2388	318.9	22.28	0.1202	187.7	6.17
SF6 DEAD TANK	0.3158	38.3	21.32	0.0526	722.3	722.27

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPTING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
MINIMUM OIL	-	-	-	-	-	-
AIR BLAST	0.2388	318.9	22.28	0.1202	187.7	6.17
SF6 DEAD TANK	0.3158	38.3	21.32	0.0526	722.3	722.27

percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	17.65%
Disconnect	20.00%

The dominant known cause(s) of **subcomponent equipment** forced outages for **200-299 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

TABLE IX
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS (1988–1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
110 - 149 kV	0.0344	187.4	18.35	0.0513	38.9	1.20
150 - 199 kV	0.0339	79.1	6.17	0.0443	145.2	1.88
200 - 299 kV	0.0738	156.1	7.37	0.1053	60.2	2.70
300 - 399 kV	0.0752	199.5	33.91	0.0595	100.9	0.98
500 - 599 kV	0.0814	116.6	8.20	0.1521	118.6	5.99
600 - 799 kV	0.2354	1315.4	22.28	0.1174	190.0	6.17

Operating Mechanisms	36.50%
Interrupting Medium	23.99%

The dominant known cause(s) of **terminal equipment** forced outages for **200–299 kV circuit breakers** and the percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	67.89%
Bus	13.71%

The dominant known cause(s) of {**subcomponent equipment** forced outages for {**300–399 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

Operating Mechanisms	48.80%
Interrupting Medium	32.20%

The dominant known cause(s) of {**terminal equipment** forced outages for {**300–399 kV circuit breakers** and the percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	62.12%

The dominant known cause(s) of {**subcomponent equipment** forced outages for {**500–599 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

Operating Mechanisms	57.55%

The dominant known cause(s) of **terminal equipment** forced outages for **500–599 kV circuit breakers** and the percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	63.63%
Bus	22.73%

The dominant known cause(s) of {**subcomponent equipment** forced outages for {**600–699 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

Operating Mechanisms	51.99%
Interrupting Medium	22.73%

The dominant known cause(s) of {**terminal equipment** forced outages for {**600–699 kV circuit breakers** and the percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	40.34%
Disconnect	28.57%

IV. CABLES

In the Canadian Electrical Association's (CEA) "Equipment Reliability Information System," the subcomponents of cable related forced outages are divided into the following subcomponents:

1) Pothead.
2) Joints.
3) Conductor.
4) Insulation System.
5) Auxiliary Equipment.
6) Other.

The identified terminal equipment categories for cable related forced outages are:

1) Control and Protection Equipment.
2) Surge Arrester.
3) Bus.
4) Disconnect.
5) Circuit Switcher.
6) Current Transformer (Free Standing).
7) Potential Devices.
8) Other.
9) Unknown.

The terminal equipment categories for cable related forced outages is identical to circuit breakers.

The frequency and duration of cable related forced outages for each voltage class is shown in Table X.

The dominant known cause(s) of {**subcomponent** forced outages for *cable related forced outages* for each voltage class

TABLE X
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CABLE (1988-1992)

	CABLE-RELATED FORCED OUTAGES			TERMINAL RELATED FORCED OUTAGES		
VOLTAGE CLASS	FREQUENCY per 100 km per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY per 100 km per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
110 - 149 kV	3.1884	39.3	3.28	0.1897	20.3	1.26
150 - 199 kV	0.0	0.0	0.0	0.0	0.0	0.0
200 - 299 kV	0.6803	176.5	8.15	0.0101	0.1	0.06
300 - 399 kV	13.3333	17.5	17.52	0.0	0.0	0.0
500 - 599 kV	0.2632	2.8	2.82	0.2000	22.6	2.00

TABLE XI
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES SHUNT REACTOR BANK (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
Up to 109 kV	2.2128	23.1	2.17	2.9362	5.3	1.43
110 - 149 kV	0.5455	38.0	5.07	2.0000	5.7	2.16
200 - 299 kV	4.0000	6.0	5.67	1.0000	1.4	1.40
600 - 799 kV	4.0000	229.9	7.18	1.0000	26.4	8.05

TABLE XII
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES SHUNT REACTOR BANK (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
Up to 109 KV	0.0344	627.8	5.13	0.1484	46.1	0.33
110 - 149 kV	0.0	0.0	0.0	0.0267	0.1	0.08
150 - 199 kV	0.0	0.0	0.0	0.0	0.0	0.0
200 - 299 kV	0.0800	89.4	12.51	0.2000	42.5	4.90
300 - 399 kV	0.0897	91.4	18.50	0.0717	3.3	0.61
500 - 599 kV	0.0314	29.2	7.80	0.0392	46.9	4.93
600 - 799 kV	0.2375	477.9	5.50	0.1029	65.8	4.17

TABLE XIII
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES SHUNT CAPACITOR BANK (1988-1992)

and their percentage of the total frequency of subcomponent forced outages are:

110-149 kV	Insulation System	58.18%
150-199 kV	No forced outages occurred	0.0%
200-299 kV	Insulation System	40.00%
300-399 kV	Insulation System	50.00%
500-599 kV	Insulation System	100.00%

The dominant known cause(s) of **{terminal equipment** forced outages for *cable related forced outages* for each voltage class and their percentage of the total frequency of terminal equipment forced outages are:

110-149 kV	Control & Protection Equipment	40.00%
	Disconnect	37.14%
150-199 kV	No forced outages occurred	0.0%
200-299 kV	Unknown	50.00%
300-399 kV	No forced outages occurred	0.0%
500-599 kV	Control & Protection Equipment	75.00%

The frequency and duration of forced outages for the following equipment are listed in their respective Tables:

1) Synchronous Compensator Table XI.
2) Shunt Reactor Bank Table XII.
3) Shunt Capacitor Bank Table XIII.
4) Series Capacitor Bank Table XIV.

Details of the subcomponents and terminal equipment

TABLE XIV
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES SERIES CAPACITOR BANK (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
Up to 109 KV	0.0067	193.3	193.27	0.0	0.0	0.0
110 - 149 kV	0.6857	57.7	5.60	0.1143	377.1	13.60
200 - 299 kV	0.0	0.0	0.0	0.0	0.0	0.0
500 - 599 kV	4.0222	41.0	12.08	2.6000	42.5	18.92
600 - 799 kV	0.2222	2.9	2.92	0.1111	10.0	10.00

forced outages for the above four equipment categories are not provided in this paper due to the scope of the paper, but these details can be found in [3].

V. CONCLUSIONS

This paper has presented a summary of the Canadian Electrical Association's "Equipment Reliability Information System Forced Outage Performance of Transmission Equipment" of the period 1988-1992. The paper presented the frequency and duration (i.e., mean and median) of forced outages of the following major equipment by voltage class:

1) Transformer Banks.
2) Circuit Breakers.
3) Cables.
4) Static Compensator.
5) Shunt Reactor Banks.
6) Shunt Capacitor Banks.
7) Series Capacitor Banks.

For all the major equipment categories, the forced outage statistics were divided into "all integral subcomponents" and "all terminal equipment" categories to provide a clear distinction between the major causes of transmission system equipment. For each major equipment category, the dominant subcomponent and dominate terminal equipment which contributed the most to the frequency of the major equipment forced outages was identified.

For transmission banks, the subcomponent and terminal equipment frequency of forced outages were of the same order of magnitude for the on-three phase element transformer bank and the three-single-phase element transformer bank. In the majority of cases, for both types of transformer banks, the mean duration was significantly greater than the median for all voltage classes. The dominant transformer bank subcomponent forced outages were "On-load Tap Changer" and the "Auxiliary Equipment" for all voltage classes. The dominant transformer terminal equipment forced outages was the "**Control and Protection Equipment**" for all voltage categories.

For circuit breakers, the higher the voltage class, the higher the frequency of forced outages for subcomponent and terminal equipment forced outages. The mean duration for subcomponent and terminal equipment forced outages was significantly higher than the median for both categories. The dominant circuit breaker subcomponent forced outages were the "Operating Mechanisms" and the "interrupting Medium." The dominant circuit breaker terminal equipment forced outage category was "**Control and Protection Equipment.**"

For cables the terminal related forced outages were significantly less than the cable related forced outages. The dominant cable subcomponent forced outage was the "Insulation System" and the dominant terminal related forced outage was again "**Control and Protection Equipment.**"

The frequency and duration of transmission equipment forced outage statistics presented in this paper provides the basis for analyzing transmission system configurations and assessing the impact of forced outages on industrial and commercial facilities (e.g., voltage sags at a given physical location, the cost of power outages, the optimum operating configuration, etc.). The methodologies for performing these studies are found in IEEE Std. 493 (IEEE Gold Book).

ACKNOWLEDGMENT

The author would like to thank the following members of the Canadian Electrical Association: M. Oprisan, E. M. Ezer, and R. A. Del Bianco for their invaluable discussions and assistance in providing me with the CEA Equipment Reliability Information System reports on Forced Outage Performance of Transmission Equipment and the Instruction Manuals for Reporting.

REFERENCES

[1] Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems, IEEE Std. 493, (IEEE Gold Book).
[2] Instruction Manual For Reporting Component Forced Outages of Transmission Equipment, Canadian Electrical Association, Suite 1600, One Westmount Square, Montreal, Quebec, H3Z 2P9.
[3] Report: Forced Outage Performance of Transmission Equipment for the Period Jan. 1, 1988-Dec. 31, 1992, Canadian Electrical Association, Suite 1600, One Westmount Square, Montreal, Quebec, H3Z 2P9.
[4] An IEEE Survey on US and Canadian Overhead Transmission Outages at 250 kV and Above, Data Analysis Task Force, Working Group on Statistics of Line Outages, General Systems Subcommittee, Transmission & Distribution committee, *IEEE Trans. Power Delivery*, vol. 9, no 1, pp. 21-39, Jan. 1994.
[5] IEEE Task Force on Line Design Characteristics, Working group on statistics of Line Outages, An IEEE Survey of Transmission Line Population and Design Characteristics, *IEEE Trans. Power Delivery*, vol. 6, pp. 1934-1945, Oct. 1991.
[6] IEEE Standard Terms for Reporting and Analyzing Outage Occurrences and Outage States of Electrical Transmission Facilities, IEEE Std. 859-1987.
[7] IEEE Task Force on the Requirements for the Survey of Line Outage Data, IEEE AT&D Working Group on Statistics of Line Outages

Background, Status and Prospects, in *Proc. 14th INTER-RAM Conf. Elec. Power Industry*, Toronto, Ontario, May 26–29, 1987, pp. 255–262.
[8] M. A. Baribeau, C. T. Driscoll, and D. McGillis, "The Canadian electrical association's equipment reliability information system," in *Proc. Third Int. Conf. Reliability of Power Supply Systems*, IEC conference publication no. 225, London, UK, Sept. 19–21, 1983, pp. 150–154.
[9] M. A. Baribeau and D. McGillis, "Analysis of transmission equipment performance based on the CEA system," in *Canadian Society for Electrical Engineering, May, 1984 Conf.*, Halifax, Nova Scotia.
[10] "Predicting transmission outages for system reliability evaluations," Electric Power Research Institute, EPRI-3880, Project 1468-2, May, 1985.
[11] M. G. Lauby, K. T. Khu, R. W. Polesky, R. E. Vandello, J. H. Doudna, P. J. Lehlman, and D. D. Elempel, "MAPP bulk transmission outage data and collection," *Trans. Power Apparatus and Systems*, vol. PAS-103, pp. 213–221, Jan. 1984.
[12] M. G. Lauby, R. P. Ludorf, J. H. Doudna, D. D. Klempel, P. J. Lehman, and C. G. Dahl, "Analysis of pooling 345 kV bulk transmission outage data between the mid-continent area power pool and Northeast utilities," *Trans. Power Apparatus and Systems*, vol. PAS-104, pp. 2427–2434, Sept. 1985.
[13] M. G. Lauby, J. H. Doudna, R. W. Polesky, P. J. Lehman, and D. D. Klempel, "Effects of pooling weather associated MAPPA bulk transmission outage data on calculated forced outage rates," *Trans. Power Apparatus and Systems*, vol. PAS-103, pp. 2345–2351, Aug. 1984.
[14] A. D. Patton, "Determination and analysis of data for reliability studies," *IEEE Trans. Power Apparatus and Systems*, vol. PAS-87, pp. 84–100, Jan. 1968.
[15] R. J. Ringlee, "Techniques for pooling outage data," *Pennsylvania Electric Association (PEA), System Planning Committee Fall Meeting*, Sharon, PA, Oct. 1967.

Don O. Koval (S'64–M'65–SM'78–F'90), for a photograph and biography, see this issue, p. XXX.

Interruption Costs, Consumer Satisfaction, and Expectations for Service Reliability

By
Michael J. Sullivan, Terry Vardell,
B. Noland Suddeth, Ali Vojdani

Paper No. 95 SM 572-8 PWRS
IEEE-PES Summer Power Meeting
Portland, Oregon
July 23–27, 1995

Interruption Costs, Customer Satisfaction and Expectations for Service Reliability

Michael J. Sullivan, Vice President
Freeman, Sullivan & Co.
San Francisco, CA 94105 USA

Terry Vardell, Manager of Market Research
Duke Power Company
Charlotte, NC 28201 USA

B. Noland Suddeth, Manager of Transmission Control
Duke Power Company
Charlotte, NC 28201 USA

Ali Vojdani, Manager of Power System Analysis
Electrical Power Research Institute
Palo Alto, CA 94304 USA

***Abstract* — This paper summarizes results of a comprehensive study of the economic value of electric service carried out by Duke Power Company in cooperation with the Electric Power Research Institute. In the study, customer interruption costs were estimated for generation, transmission and distribution outages of differing lengths occurring under varying circumstances. Interruption costs for momentary outages and voltage disturbances are also reported. In addition to these economic indicators of customer value of service, customer expectations for service reliability and power quality and their satisfaction with the service currently offered are reported. Statistical methods and procedures used in estimating interruption costs are described.**

I. Introduction

Some electric utility customers experience significant economic losses when power is interrupted or when power quality problems occur. These customers need and expect the highest quality and reliability of service that the utility can supply. On the other hand, the vast majority of utility customers experience relatively little inconvenience or cost as a result of electric outages or power quality problems. They do not desire, and are not willing to pay for, significantly improved reliability and power quality.

Increasingly, utilities are being squeezed between the conflicting demands of customers who require higher quality (and more costly) service and those who demand lower rates.

95 SM 572-8 PWRS A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the 1995 IEEE/PES Summer Meeting, July 23-27, 1995, Portland, OR. Manuscript submitted January 3, 1995; made available for printing May 5, 1995.

To compete effectively given this situation, it is important for utilities to establish a balance between the costs of improving service reliability and quality, and the economic benefits that these improvements bring to customers. This approach to reliability planning is generally called Value Based Reliability Planning (VBRP).

Value Based Reliability Planning directly takes account of the value of reliability and power quality to customers in assessing the cost effectiveness of proposed investment alternatives. Typically, VBRP planning procedures incorporate customer value of service in the planning process at the point at which investment alternatives are subjected to cost-benefit analysis. This is done by including avoided customer losses (due to outages and poor power quality) in the stream of benefits that arise from utility investments to improve reliability or power quality.

Fig. 1. provides an example of the relationship between service reliability, utility investment cost and customer interruption cost [1]. The objective of value based reliability planning is to balance the utility's investment cost against the interruption costs experienced by customers [2,3]. These costs are balanced by investing in reliability so that the Total

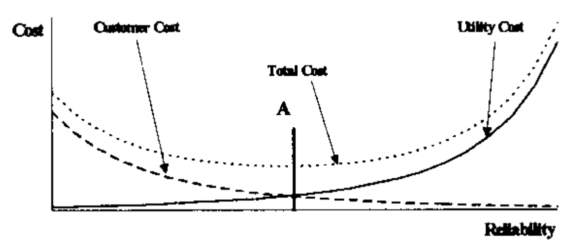


Fig. 1. Minimizing the Total Cost Of Reliability

Cost of service reliability (i.e., investment cost plus customer interruption costs) is minimized. The line A in Fig. 1. is the point on the Total Cost curve at which the Total Cost is a minimum. All utility investments with Total Costs appearing on the left side of line A are cost effective and reasonable. All those on the right side of line A are investments which increase the total cost and are unreasonable. Investment cost estimates are obtained through conventional engineering cost estimation techniques. Customer interruption cost estimates are obtained by directly surveying customers to determine the costs they experience as a result of different kinds of reliability and power quality problems.

As part of a larger effort within Duke Power Company to establish value based reliability planning, a comprehensive value of service study of Duke Power Customers was carried out in cooperation with the Electric Power Research Institute in 1992-93. In addition to interruption costs, the study measured customer satisfaction with and expectations for service reliability and quality.

II. Approach

Customer interruption costs are the economic losses customers experience as a result of interruptions of electric service or power quality problems. These costs vary from customer to customer as a function of a number of factors including:

- o the customer's dependence on electricity;
- o the nature and timing of the electric supply disturbance; and
- o the economic value of the activity being disrupted.

Consequently, to estimate customer interruption costs it is necessary to statistically survey representative samples of customers.

Procedures for statistically surveying customer interruption costs have been developed and refined by a number of utilities over the past 15 years; and in the late 1980s the Electric Power Research Institute (EPRI) co-sponsored several large scale efforts to demonstrate the estimation of outage costs using state of the art survey techniques [4]. The basic methodology used in these studies involves directly asking random samples of customers in different market segments (i.e., residential, commercial and industrial) to estimate their economic losses as a result of power reliability and quality problems commonly considered in utility planning.

Using the methods that had been developed and tested over the years by EPRI and others, information was collected from customers concerning the economic and operational impacts of a number of reliability and quality conditions. The seven outage scenarios outlined below comprise the minimum set of conditions for which information is required to support VBRP at Duke Power Company. These conditions included:

1) a one-hour Generation outage (i.e., an outage occurring at the time of system peak with advance notice;
2) a one-hour summer afternoon T&D outage;
3) a four-hour summer afternoon T&D outage;
4) a two-hour winter morning T&D outage;
5) a 1-2 second momentary outage (clear weather);
6) several 1-2 second momentary outages (occurring during a summer storm); and
7) a 15 to 20 percent voltage sag (large customers only).

Customers cannot distinguish between outages resulting from generation capacity shortfalls (generation outages) and those resulting from failures on the transmission or distribution system (T&D outages). Nevertheless, the <u>conditions</u> that customers experience during outages originating in the generation system are very different from the conditions they experience for outages originating on the transmission or distribution system; and as will become clear below, these different conditions result in very different outage costs.

Outages originating on the transmission and distribution system generally occur without warning and can last anywhere from microseconds to many hours (even days). Outages resulting from generation capacity shortfalls are different in several important respects. Generation capacity shortfalls do not cause the collapse of the utility system because the operation of the system during generation shortfalls is governed by emergency operating procedures. These procedures dictate ameliorative actions that the utility will take when operating reserves are forecasted to fall below specified levels. Among the actions that are usually called for are public appeals for voluntary curtailments and if the situation continues to worsen, interruption of randomly selected retail circuits preceded by radio and television announcements. These interruptions are designed to last a fixed period of time (usually one hour) and are imposed in rotating fashion. Because the duration of the outage is fixed and known and because the customer receives advance notice of its onset, the costs resulting from generation outages are significantly lower than the costs that customers would otherwise experience.

Table 1. summarizes critical features of customer interruption cost surveys conducted during the study. The survey designs, sample designs and study procedures differed by market segment and customer size. Residential customers were surveyed by mail. Small and medium sized industrial and commercial customers were surveyed using a combination of telephone and mail; and large industrial and commercial customers were surveyed in-person by experienced cost estimators.

III. Interruption Cost Summary

In the event of a generation outage, the average cost per kWh of unserved energy on the Duke Power System is estimated to be $7.79 (1992). Table 2. summarizes average customer interruption costs per event and per kWh for summer afternoon outages of one hour duration. The generation outage occurs with one-hour advance notice via radio and television announcements by the utility. Using the sample sizes and measurement techniques applied in this study, there is only a five percent chance that true system-wide generation outage costs are below $5.38 per kWh or above $10.10 per kWh.

Commercial and industrial customers experience much higher interruption costs than residential customers. In Table 2, it is apparent that residential customer interruption costs are significantly lower than those of either commercial or industrial customers. For an outage lasting one hour on a summer afternoon originating in the transmission or distribution system, the average residential customer would experience an interruption cost of $5.39 (or about $2.07 per coincident kWh of residential customer load). For the same outage, the average commercial customer would experience a cost of $1,317 (or about $45.82 per coincident kWh of commercial customer load). For industrial customers, the average cost of this outage is estimated to be $9,404 (or about $7.61 per coincident kWh of industrial customer load). Overall the average customer cost per unserved kWh for a one hour outage without advance notice is estimated to be $16.15 (1993).

Interruption costs vary from customer to customer depending on a number of factors. Fig. 2a. and Fig. 2b. display the distribution of customer interruption costs for residential, commercial and industrial customers for a one-hour outage on a summer afternoon without advance notice. Residential customer interruption costs range from $0 to $64. Commercial customer interruption costs range from $0 to over $100,000, and industrial customer interruption costs range from $0 to over $1,000,000.

Differences in interruption costs among commercial and industrial customers are systematic and can be predicted from related production factors (i.e., the customer's business type, size and production technology). Using these production factors, multiple regression models were developed for predicting customer interruption costs. Fig. 3. shows the relationship between predicted and actual interruption costs for a multiple regression model predicting customer interruption costs from these factors. Predictions from the regression model are not perfect, but they are significantly more accurate than predictions based only on

Table 1. Duke Power Company - Value of Service Study Approach and Methodology

Duke Power Customer Class	Customer Class Characteristics	Sample Design	Outage Cost Estimation Methods	Customers Contacted	Customers Responded	Response Rate
Residential	All Residential Customer Accounts	Random Sample Stratified by Geographic Location and Prior Reliability	Mail Survey, using Willingness to Pay measures with High Control and Low Control variations	2,187	1,584	72%
Large Industrial and Commercial	Customers that Receive Power at Non-Residential Rate Schedules with Demand > 1MW or Receiving Power at Transmission Voltages	Random Sample Stratified by Business Type and Transmission or Distribution Voltage Levels	On-Site Surveying Using Direct Worth Outage Cost Calculations	299	210	70%
Small and Medium Industrial and Commercial	Customers that Receive Power at Non-Residential Rate Schedules with Demand <1MW and are on Distribution Circuits	Random Sample Stratified by Business Type and Electrical Demand	Combination of Telephone and Mail Survey Using Direct Worth Outage Cost Estimates	2,797	1,080	40%

Table 2. Customer Outage Cost Summary

Market Segment	Generation Outage Mean Outage Cost	Transmission or Distribution Outage Mean Outage Cost
Residential Customers		
Cost Per Event	\$4.91	\$5.39
Cost Per Peak kWh	\$1.88	\$2.07
Commercial Customers		
Cost Per Event	\$604.19	\$1,317.21
Cost Per Peak kWh	\$21.02	\$45.82
Industrial Customers		
Cost Per Event	\$4,443.00	\$9,403.55
Cost Per Peak kWh	\$3.60	\$7.61
System Wide		
Cost Per Event	n/a	n/a
Cost Per Peak kWh	\$7.79	\$16.15

Michael J. Sullivan, "Volume Five: Outage Cost Summary", in Final Report For Value Of Service Study, December 1992

market segment means (i.e., the mean for commercial or industrial customers). For example, multiple R^2s for regression models predicting outage costs arising from different kinds of outages ranged from .67 to .34. That is, these models explain between 34 and 67 percent of the variation in outage costs about the averages for the market segments — a statistically significant improvement over the predictive power arising from market segment alone.

Since much less information is required to estimate customer outage costs from the parameters in the regression model, it is possible to calculate customer specific outage cost estimates for all large customers (from regression models) and thus to obtain detailed estimates of customer outage costs without the expense of on-site surveys of all customers. This approach is being used by Duke Power Company to calculate circuit specific outage costs including unique estimates for each of its 1,000 largest customers.

Although less of the variation in residential interruption cost is accounted for by variation in other household attributes, significant statistical associations are found between residential customer interruption costs, the size of the household and the age of its inhabitants. In general, the older the members of a household, the lower the household's average interruption cost. When children are present, customer interruption costs are significantly higher.

Circuit level interruption costs should be used when applying interruption cost information to transmission and distribution planning problems. While system average interruption cost estimates are meaningful and useful for generation planning, significant errors can be made by applying system average figures to particular circuits. Because of the variation that exists across circuits in the distribution of customers by market segment and size, customer interruption costs for particular circuits may deviate dramatically from system averages.

From the individual customer's point of view, generation outages (i.e.,. those including advance warning) are inherently less costly than transmission and distribution outages (i.e., those without warning). Advance warning significantly lowers the costs of outages for commercial and industrial customers. Table 3. illustrates the effect of advance notice on customer outage costs.

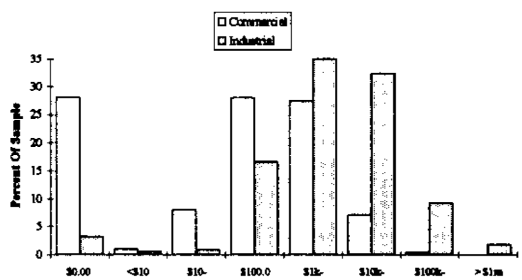


Fig. 2a. Commercial and Industrial Customers

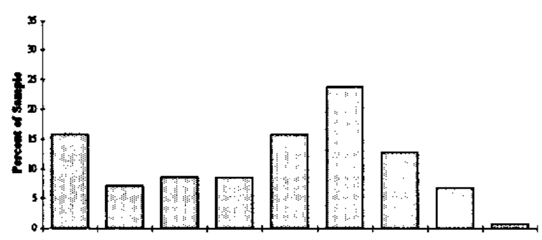


Fig. 2b. Residential Customers

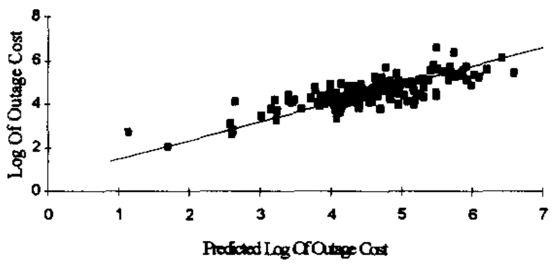


Fig. 3. Prediction of Customer Outage Costs

Given one hour advance notice, the average large commercial customer can reduce its interruption cost by 35 percent, from $22,506 to $14,574. For large industrial customers the savings due to advance notice are even greater. Given one hour advance notice, the average large industrial customer can reduce its interruption cost by 43 percent, from $46,695 to $26,582.

Voltage sags of 20 percent for less than 30 cycles can result in significant interruption costs for about 10 percent of Duke Power's largest industrial and commercial customers. On average, large commercial and industrial customers estimated that a voltage sag would cost about $7,694. However, slightly less than 50 percent of the large customers surveyed said that they would experience no losses as a result of a voltage sag. The interruption costs estimates provided by the remaining 50 percent of customers ranged from a low of $13 to a high of about $285,000. Ten percent of the large customers surveyed estimated their losses from a voltage sag would be in excess of $23,600. For customers who said that they would experience costs as a result of a voltage sag, the average cost was estimated to be $60,407.

Momentary interruptions can result in significant interruption costs for most of Duke Power's large commercial and industrial customers. On average, large customers estimated they would experience costs of $11,027 as a result of a 1 to 2 second momentary interruption on a summer afternoon. Approximately 35 percent said they would experience no losses as a result of a 1 to 2 second outage. Fifty percent of the large customers said that a momentary interruption of 1 to 2 seconds would result in outage costs in excess of $1,500; and ten percent of large customers said that their costs in the event of a momentary outage would exceed $45,130. For customers who said that they would experience costs as a result of a momentary outage, the average cost was estimated to be $72,426.

Table 3. Customer Interruption Costs With and Without Advance Notice

Customer Class	With Notice	W/O Notice
Large Commercial	$14,574	$22,506
Large Industrial	$26,582	$46,695

IV. Customer Expectations For Service Reliability

Most customers understand that it is virtually impossible to provide perfect power supply reliability and power quality. However, they differ dramatically in their expectations for the utility's performance along these dimensions.

Large commercial and industrial customers expect nearly perfect service reliability. Most of the large commercial and industrial customers in the study were served at transmission voltages. These customers experience almost no outages. From their reactions to the survey, it is reasonable to conclude that most large commercial and industrial customers probably do not consider any number of outages of any duration to be acceptable.

Small and medium sized commercial and industrial customers expect significantly higher reliability than residential customers. Customers on primary and secondary distribution circuits were asked to indicate the number of outages (of different durations) that they consider to be acceptable in a given year. The objective of this battery of questions was to measure the customer's desired level of service reliability in non-economic terms. The outage durations studied included momentaries, short outages (i.e., less than one hour) and long outages (i.e., outages lasting one to four hours). In the survey, respondents could indicate that they thought outages of the above durations would be acceptable at one of the following intervals: daily, weekly, monthly, every few months, twice a year, once a year, and none of the above.

Fig. 4a. and Fig. 4b. compare the answers to the above question given by residential and small and medium sized commercial and industrial customers. The figures show that residential customers have significantly lower expectations for service reliability than commercial and industrial customers. For example, Fig. 4a. shows that fifty percent of residential customers consider two or less extended outages per year to be an acceptable level of service. On the other hand, fifty percent of commercial and industrial customers expect one or fewer outages per year. That is, the median

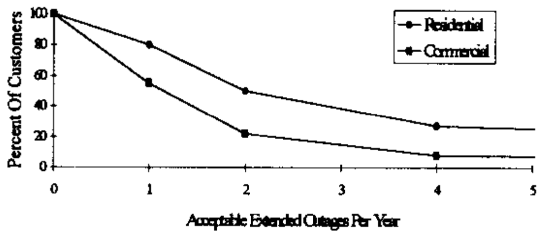


Fig. 4a. Acceptable Number of Extended Outages

commercial and industrial customer expects service to be about twice as reliable as the median residential customer.

The difference between expectations for service reliability for non-residential and residential customers is even more pronounced for momentary outages. Fig. 4b. shows that the median residential customer considers service to be acceptable if the number of momentary outages is less than about 38 per year -- about once every ten days. On the other hand, the median non-residential customer expects fewer than 12 outages per year -- about one per month. Here non-residential customers expect or desire service that is about three times as reliable as that desired by residential customers.

V. Customer Satisfaction

The satisfaction of customers with service reliability was measured in all three studies to ensure that the issue of customer satisfaction could be addressed. The customer satisfaction measures used in the surveys were comparable to those used on other studies of Duke Power customers.

The relationship between the reliability of utility service and residential customer satisfaction is more complicated than it might appear at first. The results of this survey indicate that reliability history has no direct effect on a customer's satisfaction with utility service. That is, customers who receive relatively less reliable service are no less satisfied than other customers who receive higher reliability service. Fig. 5. shows that there are relatively small differences in the levels of satisfaction for customers in the survey sampled from circuits with dramatically different prior reliability histories.

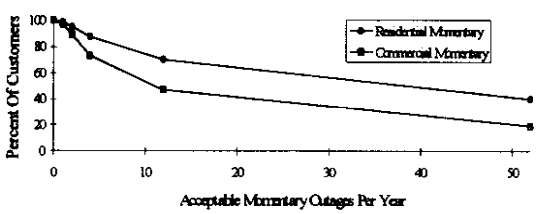


Fig. 4b. Acceptable Number of Momentary Outages

Residential customer satisfaction is determined by the customer's perception of their service reliability, not by their actual service reliability. Residential customer's perception of the reliability of their service is highly correlated with their satisfaction. Customers who perceive that they are experiencing relatively high numbers of momentary or sustained outages are significantly less satisfied than customers who believe that they are not receiving relatively high numbers of outages.

Customer's perception of the reliability of their electric service is influenced by the reliability of their service, but most residential customers cannot distinguish high reliability service from low reliability service. Customers who experience relatively small numbers of momentary and sustained outages are significantly more likely to say that the number of outages they experience is very low than are customers who experience these kinds of outages more frequently. However, the relationship between perceived service reliability and actual service reliability is tenuous. Only customers in the extremes of the reliability distribution appear to be able to discriminate their level of service reliability, and then only imperfectly.

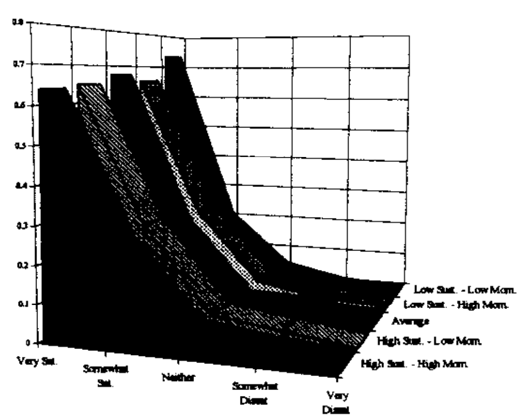


Fig. 5. Residential Satisfaction

The effect of actual service reliability on customer satisfaction is indirect, based on the customer's perception of the reliability of its service. Many other factors affect the customer's perception of the reliability of their service besides the actual level of reliability that they experience.

VI. Conclusions

This study shows that customer interruption costs vary systematically and predictably as a function of customer type and size and within commercial and industrial customers by the processes, equipment and products being made and sold. It documents the ameliorative effects of advance warning on interruption costs arising from generation outages and suggests that electric emergency planning may be a highly cost effective alternative to investment in new generation. Because there are significant differences across utility circuits in the numbers and types of customers served, this study suggests that it is inappropriate to apply system wide interruption cost estimates to transmission and distribution planning problems. Work is ongoing at Duke Power Company and the Electric Power Research Institute to develop interruption cost estimates that are appropriate for these applications.

References

[1] Allan R. and R. Billinton, "Power System Reliability and its Assessment: Part 3, distribution systems and economic considerations", Power Engineering Journal, August 1993

[2] Burns S. and G. Gross, "Value of Service Reliability" , IEEE Transactions on Power Systems, August 1990, Vol . 5 No. 3

[3] Munasinghe M. and M. Gellerson, "Economic Criteria For Optimizing Power System Reliability Levels", Bell Journal of Economics, Spring 1979, 353-365

[4] *Cost-Benefit Analysis of Power System Reliability: Determination of Interruption Costs - Vol. 1: Measurement Methods and Potential Applications in Reliability Cost-Benefit Analysis*, EPRI EL-6791, April 1990

Biographies

Michael J. Sullivan has a Ph. D. in Sociology from Washington State University. Prior to founding Freeman, Sullivan & Co., he was Operations Coordinator for Load Management at Pacific Gas and Electric Company and a Lecturer at the Hass Business School at the University of California, Berkeley. He has over 20 years experience directing large scale statistical surveys designed to estimate population parameters for use in engineering and scientific modeling and forecasting. He is currently Vice President of Practice at Freeman, Sullivan & Co.

Terry Vardell has an MBA from the University of South Florida. He has over 25 years experience as a market researcher in the utility, banking and retail service markets. He joined Duke Power Company as a project manager in Market Research in 1991 and is now Manager of Market Research.

B. Noland Suddeth earned a M. S. and a B. S. degree in electrical engineering from Clemson University in 1984 and 1982, respectively. Subsequently, he joined Duke Power Company in Charlotte, NC as an engineer in System Planning working through Generation, Distribution and Bulk Power Planning over a nine year period. He is currently Manager of the Transmission Control Center at Duke. Mr. Suddeth is also a Lecturer at the University of North Carolina at Charlotte. Mr. Suddeth is a registered Professional Engineer in NC and SC and is a member of IEEE.

Ali F. Vojdani earned a Ph.D. degree in Electrical Engineering from McGill University in Montreal, Canada in 1982. Subsequently, he joined Pacific Gas and Electric Company, providing analytical and computer services to operations and planning departments as Supervisor of Systems Engineering Group until 1993. He is currently Manager of Power System Analysis at Electric Power Research Institute. Dr. Vojdani is a Senior Member of IEEE and a member of Technical Committee of Power Industry Computer Applications (PICA) Conference.

Survey Results of Low-Voltage Breakers as Found During Maintenance Testing

By
Pat O'Donnell

IEEE Industrial and Commercial Power Systems
Technical Conference
New Orleans
May 6–9, 1996

Reprint from IEEE Conference Record
96CH35920, pp. 1–4

Survey Results of Low Voltage Circuit Breakers as Found During Maintenance Testing

Working Group Report

Pat O'Donnell
El Paso Natural Gas Co.
El Paso, TX
(Coordinating Author)

Other Working Group Members: W.F. Braun, C.R. Heising, P.P. Khera,
M. Kornblit, K.D. McDonald

***Abstract* - The Power Systems Reliability Subcommittee strives to maintain current reliability data on major electrical equipment to assist the industry in accomplishing realistic and meaningful reliability studies. This paper presents results of a low voltage circuit breaker reliability survey achieved through use of available results from testing during preventive maintenance. A substantial number of test results were obtained to allow credible results for a few different circuit breaker categories. A similar set of results was published in a paper[1] for the 1990 Industry Applications Society Conference. Most of these results have been incorporated into this new expanded effort.**

INTRODUCTION

Results of a low voltage circuit breaker reliability survey, obtained from circuit breaker preventive maintenance tests are presented here. The results show differences between various categories and what components failed, allowing the reader to judge with some degree of confidence, the weaknesses and strengths of the circuit breakers. Since the results are taken from circuit breaker tests, failure rate as a function of time was not possible. However, because of the nature of the operation of this equipment type, these forms of data and results are of value since often a failure or pending failure is not evident until a test is conducted.

In keeping with the policy of the Power Systems Reliability Subcommittee, survey results of this type do not identify manufacturers, do not promote any types or designs nor are the results intended to draw definite conclusions. This is left to the reader.

The following tables reflect available data from the tests, but only where sufficient data were available to present credible results (in the judgment of this working group).

GENERAL

Certain categories were possible to present, as evidenced in the tables to follow, and some comment is beneficial here in understanding the results. Many tests described certain circuit breakers as being in "new" condition or appearing "new". These were broken out allowing comparison to "old" circuit breakers or those not identified as in "new" condition. Some circuit breakers were tested more than once. Number of tests are shown and were counted separately if approximately 3 years or more apart. It is important to remember the results here are taken from tests that did not identify service conditions, age, or time of use. The tables below show number of tests and also number of circuit breakers to allow evaluation based on either. The failure modes available from the tests are defined as follows.

Trip Unit : failed to operate - repaired or replaced (Note: where calibration

	could not be corrected by readjustment and required replacement, a trip unit failure was counted)
Trip Calibration :	not able to trip within specified current and time range -required readjustment
Mechanical :	springs, arms, levers, hardened lubricant, etc. - repaired or replaced
Power Contacts :	alignment, incorrect pressure, pitted, etc. - repaired or replaced
Arc Chutes :	chipped, cracked, burned, etc. - repaired or replaced
Auxiliary Device :	auxiliary contacts, indicators, pushbuttons, etc. - repaired or replaced

OVERALL SUMMARY (TABLE 1)

Table 1 shows all circuit breakers tested and what failed during a test. The trip unit and trip calibration were the highest in failures, the percentage of failures being 2 or more times that of other failure modes.

TABLE 1

Total No. Bkrs	1174	
Total No. Tests	1989	
Total No. Failures at Test	294	
	No. of Flr's	% of Tests
Failed Component:		
Trip Unit	109	5.5
Trip Calibration	84	4.4
Mechanical	45	2.3
Power Contacts	44	2.2
Arc Chutes	12	0.6
Auxiliary Device	10	0.5
Total No. Failed Components	*304	15.3

* 10 circuit breakers had 2 failed components during one test

SOLID STATE TRIP UNITS VS ELECTROMECHANICAL TRIP UNITS - (TABLE 2)

Table 2 compares solid state (S/S) trip units to electromechanical (EM) type. Results show the EM breaker types with a higher percentage of failures (or unacceptable operation) of all components. As some would predict, the EM trip units experienced substantially more failures than the S/S type, approximately twice the percentage. Since some circuit breakers were described in the test results as in "new" condition, these have been broken out to show any influence this condition may have had on the failures. There was no test data clearly showing EM type as "new", so it can be assumed that none of these appeared in "new" condition. The results show that the "new" S/S type, although showing some expected influence on the results, if broken out separately, would still not change this observation of EM types showing a higher percentage of failures. Another observation is that for all circuit breakers with S/S trip types, there is a more even distribution of percentage of failures over the different failure modes than for E/M types which clearly have the highest percentage of failures associated with the trip units.

TABLE 2

Trip Unit Type	All EM		All S/S		New S/S	
Total No. of Bkrs	662		512		99	
Total No. of Tests	1054		935		176	
Failed Component	# of Flr's	% of Tests	# of Flr's	% of Tests	# of Flr's	% of Tests
Trip Unit	81	7.7	28	3.0	*2	1.1
Trip Calibration	60	5.7	24	2.6	*0	0.0
Mechanical	26	2.5	19	2.0	*4	2.3
Power Contacts	25	2.4	19	2.0	*5	2.8
Arc Chutes	*6	0.6	*6	0.6	*0	0.0
Auxiliary Device	*6	0.6	*4	0.4	*0	0.0
Total No. Failures	204	19.4	100	10.7	11	6.2

* Small sample size - less than 8 failures

SOLID STATE vs. ELECTROMECHANICAL ACCORDING TO FRAME SIZE (TABLE 3)

Table 3 shows how circuit breakers with S/S and EM trip units compare according to frame size. The 600 amp and 800 amp frame sizes are combined since very little difference is expected in applications. Larger frame sizes include 4000 amp, but the total number breakers and tests warranted combining all sizes 1600 amp and above. Results show a significant difference in percentage of failures between the smaller and larger frame sizes for circuit breakers with EM trip units, with the larger frame sizes higher than that of the smaller sizes. Frame size shows less effect on the difference between large and small circuit breakers with S/S trip types. EM trip units still show an obviously higher percentage of failures when compared to S/S type.

TABLE 3

Frame Size	600 A & 800 A				1600 A & Above			
Trip Unit Type	EM		S/S		EM		S/S	
No. of Breakers	464		380		198		132	
No. of Tests	842		778		212		157	
Failed Component	# of Flr's	% of Tests	# of Flr's	% of Tests	# of Flr's	% of Tests	# of Flr's	%of Tests
Trip Unit	50	5.9	20	2.6	31	4.6	8	5.1
Trip Calibration	41	4.9	22	2.8	19	9.0	*2	1.3
Mechanical	17	2.0	16	2.1	*6	2.8	*3	1.9
Power Contacts	16	1.9	19	2.4	*6	2.8	*0	0.0
Arc Chutes	*6	0.7	*4	0.5	*0	0.0	*0	0.0
Auxiliary Device	*2	0.2	*3	0.4	*2	0.9	*1	0.6
Total No. Failures	132	15.7	84	10.8	64	30.2	14	8.9

* Small sample size - less than 8 failures

SOLID STATE vs ELECTROMECHANICAL TRIP CALIBRATION FAILURES (TABLE 4)

Table 4 shows the failure relationship between the long time, short time and instantaneous settings of trip units. Some circuit breakers had more than one time setting out of calibration, evidenced by the total exceeding the total of trip calibration failures in tables above. Some circuit breakers did not have all 3 time settings available, but practically all had instantaneous settings with the exception of a few. The results show no calibration failures for the instantaneous settings for S/S trip units.

TABLE 4

Trip Unit Type	All EM		All S/S	
Total No. of Bkrs	662		512	
Total No. of Tests	1054		935	
Trip Calib. Failure	# of Flr's	% of Tests	# of Flr's	% of Tests
Long Time	45	4.3	14	1.5
Short Time	*1	0.1	11	1.2
Instantaneous	29	2.8	*0	0.0
**Total	75	7.1	25	2.7

* Small sample size - less than 8 failures
** Some circuit breakers had more than one time setting out of calibration

OBSERVATIONS/CONCLUSIONS

A significant observation from the results of this survey is that, for all circuit breakers, the percent of unacceptable operations of EM trip units were more than twice those with S/S trip units. This included both failure of the trip unit to operate and failure due to calibration.

EM trip units for circuit breakers rated 1600 amp and above, combined, experienced more than twice the percent of unacceptable operations as those rated 600 amp and 800 amp, combined. Again, this included both failure of the trip unit to operate and failure due to calibration.

For all circuit breakers, both percent of unacceptable operation of trip units and calibration were much higher than the other failure modes. Mechanical operation failures and power contact failures experienced the same percentage for both EM and S/S type circuit breakers.

ACKNOWLEDGMENT

Appreciation is expressed to Kelly R. O'Donnell, University of Texas at San Antonio student, for contributions in data gathering and input.

REFERENCES

[1] "Maintaining the Integrity of a Changing Power System", by M.J. Kornblit, IEEE Industry Applications Society, Oct. 7 - 12, 1990, Seattle, IEEE Catalog No. 90CH2935-9, pp 1357 - 1362

Survey of Reliability and Availability Information for Power Distribution, Power Generation, and HVAC Components for Commercial, Industrial, and Utility Installations

By
Peyton S. Hale, Jr., and Robert G. Arno

IEEE Industrial and Commercial Power Systems
Technical Conference
Clearwater, Florida
May 7–11, 2005

Reprint from IEEE Conference Record
ISBN 0-7803-5843-0,

SURVEY OF RELIABILITY AND AVAILABILITY INFORMATION FOR POWER DISTRIBUTION, POWER GENERATION, AND HVAC COMPONENTS FOR COMMERCIAL, INDUSTRIAL, AND UTILITY INSTALLATIONS

Mr. Peyton S. Hale, Jr.
U.S. Army Corps of Engineers
Special Missions Office
Power Reliability Enhancement Program (PREP)
10115 Gridley Road
Fort Belvoir, VA 22060-5859

Mr. Robert G. Arno
Reliability Analysis Center (RAC)
201 Mill Street
Rome, NY 13440-6916

Abstract

This paper presents the culmination of a 24,000 man-hour effort to collect operational and maintenance data on 204 power generation, power distribution and HVAC items, including gas turbine generators, diesel engine generators, electrical switchgear, cables, circuit breakers, boilers, piping, valves, pumps, motors and chillers. The data collection process and the resultant data are the subject of this paper.

The Power Reliability Enhancement Program established the data collection effort to determine the effects of "new technology" equipment, i.e., equipment installed after 1971, on reliability and availability. Previous data collection efforts were completed in the early 1970's using data collected in the 1950's and 1960's. The primary purpose of the data collection effort was to provide more current equipment reliability and availability data when performing a facility reliability/availability assessment. Information was obtained on a variety of commercial and industrial facility types (including office buildings, hospitals, water treatment facilities, prisons, utilities, manufacturing facilities, school universities and bank computer centers), with varying degrees of maintenance quality.

Data collection guidelines and goals were established to ensure that sufficient operational and maintenance data were collected for statistically valid analysis. Minimums of 3.5 million calendar hours were established for each component. Time-to-failure data, helpful in model development, were collected, when available, to determine device failure characteristics. A database system, with flexible output capabilities, was developed to track both the equipment information (containing over 6,000 records of operational and maintenance data) and the contact information (containing over 3,500 records identifying information sources). The levels of data quality and maintenance quality were assessed during the analysis phase of the project.

The results indicated that the maintenance quality level was a major predictor of equipment availability, therefore, the availability values presented represent an average maintenance program across all the data sources. In addition, the information obtained can aid facility designers and engineers in evaluating different designs to minimize production/mission failure and to estimate the down times associated with various systems or sub-systems. Facility types that require more maintenance time and systems that may benefit from redundancy or replacement can also be identified.

The U.S. Army Corps of Engineers, Power Reliability Enhancement Program, located in Fort Belvoir, VA, sponsored this two-year program. The work was accomplished by the Reliability Analysis Center (RAC) in Rome, NY.

I. INTRODUCTION

The U.S. Army Corps of Engineers, Power Reliability Enhancement Program (PREP) sponsored a study of the reliability, availability and maintainability characteristics of 204-power generation, power distribution, and Heating Ventilation and Air Conditioning (HVAC) items. This paper describes the data collection and summarization of all 204 items. The Reliability Analysis Center (RAC), a DoD Information Analysis Center operated by IIT Research Institute, in Rome New York, began the work in October 1991 and delivered the final report in early 1994.

II. BACKGROUND

The Power Reliability Enhancement Program established a utility system availability goal of 0.999999 (31.5 sec/yr. downtime) at Command, Control, Communication, Computers and Intelligence facilities worldwide. The methodology PREP used in calculating the system reliability and availability was a Boolean algebra based modeling technique using individual equipment reliability values to produce the system model.

Prior to this study, PREP based its predictions on component reliability and availability information developed in the early 1970's that had been compiled from multiple sources. However, PREP had discovered problems with using this information source since the information contradicted itself and contained some confusing data. In addition, the database did not fully address maintenance. Therefore, it became apparent that the data needed to be updated.

III. DATABASE DEVELOPMENT

A computerized system named PREPIS (Power Reliability Enhancement Program Information System) was developed to assist technical staff in organizing, tracking, analyzing, and reporting all of the technical and contact information during the execution of this PREP program. The two major components in PREPIS are:

1. Contact records: contains site information; it is comprised of 6208 contact records.
2. Equipment records: contains performance and maintenance information; it includes 4043 equipment records.
3. This comprehensive database system was organized functionally to support the following tasks:
   - Record individual site information
   - Prioritize site visits
   - Collect and organize site data
   - Data input and verification
   - Data summarization and analysis
   - Report generation

The output record generator contains several "canned" reports designed for data summary and availability calculations. Some of the reports are designed to allow the user the flexibility to select a multitude of query topics. The format of the report generator allows easy construction of custom reports for individual needs.

This database, developed in 1991, was adequate for the task. As new, more efficient database tools were developed it became apparent that a more portable, user friendly database tool was needed. In addition several inquiries of the database resulted in a significant effort to recreate data reports to satisfy requests. A better method was sought to minimize this time.

RAC began the arduous task in 1998 of creating a common database and has transferred the data into Microsoft Office Access database allowing the user the ability to develop customized data extraction scenarios on a PC. The database can now be placed on a CD and transferred to anyone with Microsoft Office Access.

Database Information

In order to collect statistically valid data it was important that a stratified survey of different facility categories, applications and operating conditions be conducted. Guidelines were developed to assist in the selection of potential sites. These guidelines include:

1. Locations surveyed were required to have varying degrees of maintenance practices.
2. A number of sites for each facility category were predetermined; this was required to eliminate any skewing of the data caused by the influence of limited data.
3. Component size was also a basis of site selection to ensure that similar technologies were being compared.
4. Equipment age was also considered to ensure that data from both the newer high-efficiency generation of equipment and the older technology generation were included.

The first of these was included because it is known that maintenance policies and practices directly affect equipment availability. High levels of maintenance lower availability, but have the potential to increase reliability. Too little maintenance raises availability, but has the potential to decrease reliability. During a prolonged period of operation time with little maintenance, availability and reliability both decrease drastically. The amount of maintenance performed can drastically affect the performance parameters being collected.

A process of identification and certification of data was developed to ensure that each data collection trip was successful. Minimum requirements for data were established to ensure a sound statistical basis for the analysis:

- A minimum of five years of operational data was collected.
- A minimum sample size of 40 with a maximum site allocation of 10 items each was imposed.
- A minimum of 3.5 million calendar hours total for each component was established.

Data Contacts

Contacts were the key to the success of this program. The cooperation and support of the people involved from the many facilities, even during times of budget and personnel reduction is demonstrated in the quality of data received to support the PREP.

A concerted effort was employed to develop an extensive contact database using manufacturers, facilities, societies, and locations of any potential data contributor utilizing PREP components. Manufacturers were contacted not only for contacts, but also for any warranty data that may be available. A total of 25 manufacturers participated, including Caterpillar, Westinghouse Electric, EMD, and MFG Systems Corporation. A total of 25 professional societies were contacted, including:

- American Gas Association
- National Association of Power Engineers
- American Society of Mechanical Engineers
- Association of Physical Plant Administrators
- Association of Energy Engineers

IV. DATA SUMMARIZATION AND CLASSIFICATION

Data Completeness

As with every data collection program, there are varying degrees of completeness in the data gathered. Some data sources had complete records and could give statistics on operational characteristics on every piece of equipment from installation date to that current moment of time. More often, the only items tracked were major items such as cooling towers and boilers. Data for items such as valves and filters were not usually recorded. Other problems included incomplete or non-current versions of the equipment's blue prints. Several RAC technicians manually developed parts lists, recording data from nameplates and relying on facility engineers for component descriptions.

It became important to categorize the different levels of data completeness to ensure that the final data collection included fair data representation for each component. To quantify this data completion (or quality) index, RAC identified these four levels:

1. Perfect Data: Data needed for a valid, complete reliability study, including a parts list, failure history data with time-to-failure statistics, parts description data, operational periods, and ten continuous years of recorded data. No engineering judgment or data extrapolation is required. The PREPIS equipment record database is comprised of 10% to 20% of this type of data.
2. Not Perfect Data: Data with no serious flaws, but the data collection process demanded additional time to ensure useful information was gathered. Examples include parts list determined by inspection, incomplete blueprints or less than ten years of data. The PREPIS equipment record database contains 35% to 40% of this type of data.
3. Verbal/Inspection Data: Data with serious gaps that required additional documentation and verification prior to its inclusion in the database. Items included were typically major items, such as generator sets and boilers. Senior maintenance personnel were interviewed to extract the necessary information to fill the data gaps. These interviews were used as support documentation to recorded data, not as data source information. About 25% of this type of data exist in the PREPIS equipment record database.
4. Soft Data: Data that relied on the memories of experienced maintenance personnel from the participating facility; it was often extracted from log books containing maintenance personnel entries, filing cabinets with work order forms, and repair records when outside repair support was needed. Engineering judgment was often used to determine numerous performance parameters. This type of data was the most difficult and time consuming to summarize and was only used when no other data sources were available. The PREPIS equipment record database is comprised of 10% to 15% of this type of data.

Maintenance Policy

The major intent of the data collection effort was to minimize the effects of maintenance policies and procedures on the calculated availability values by collecting data from a variety of locations having various maintenance policies. RAC personnel developed a code to categorize each facility's maintenance policies and procedures into one of three levels:

Code "1": <u>Above average</u> maintenance policy. The facility not only followed a scheduled, preventative maintenance policy that was equivalent or similar to the manufacturer's suggested policy, but also went beyond it, such as using redundant units, specialized equipment tests (thermograph, vibration analysis, oil analysis), complete spare parts kits for equipment, and so on.

Code "2": <u>Average</u> maintenance policy. Facility used either in-house maintenance crews performing scheduled, preventative maintenance according to the equipment manufacturer's suggested PM schedule or a combination of in-house maintenance crews and outside contractors. In both cases, it was verified that they did actually follow a fairly rigid schedule.

Code "3": <u>Below average</u> maintenance policy. Facility's actual policy was less than average. It may have instituted a scheduled maintenance policy but not followed it or it may have had no maintenance policy. Symptoms such as leaky valves with rags tied around them, dirty air filters, squeaky bearings, lose belts, and general house keeping because of unavailable manpower were typical signs that maintenance at a facility was less than desirable.

Each location was then compared to each other and to the average maintenance policy. Overall, the facilities that RAC visited practiced an average level of maintenance; that is, they adhered to the manufacturers recommended maintenance policy. RAC looked at approximately the same number of facilities that had below average maintenance policies as those facilities that had an above average maintenance policy.

Results

Attached to this paper are the 204 components representing the PREP database. It is presented in a hierarchical structure to provide the analyst with numeric options if the exact component is not identified. As an example, the CATEGORY of Accumulator is comprised of two CLASSES (Pressurized and Unpressurized). Each of the CLASSES is comprised of individual data points. Reliability numeric is derived for each data point listed within a CLASS and displayed in columns in the database report.

The numeric is then rolled-up to the CLASS level to indicate a combination of information within each CLASS. Subsequently the data from the CLASS level is rolled-up

into the CATEGORY level. The reliability numeric becomes more generically applied to the item as the information is rolled-up to the next higher level. Where we had various sizes for example, transformer capacities, information was combined to create a general transformer number.

Table 1 is provided to help you understand and properly apply the data categories in your analysis. The summary information calculated from the individual equipment records is also included.

Definitions of each category are given below. These definitions are referenced in several reliability publications and the formulas can be verified in the RAC Toolkit for commercial practices, page 12, or MIL-STD-339, or in the IEEE standard definition publication. Definitions include the following:

(MDT) = Mean Down Time is the average down time caused by scheduled and unscheduled maintenance, including any logistics time.

(MTBM) = Mean Time Between Maintenance is the average time between scheduled and unscheduled maintenance, including logistics time.

(Tp) = Total Period is the Calendar time over which data for the item was collected.

(Rdt) = Repair Down Time is the Total Down Time for Repairs Due to failures (Unscheduled Maintenance).

(Mdt) = Maintenance Down Time is the Total Down Time for scheduled maintenance (including logistics time).

8760 = Total Hours in a Year (non-leapyear).

Ao = Operational Availability considers down time for Scheduled (repair due to failures) and Unscheduled maintenance, including Logistics time. Reference RAC Toolkit, MIL-STD-338, and IEEE Dictionary.

Ai = Inherent Availability considers down time for repair to failures only, no logistics time. Reference RAC Toolkit, MIL-STD-338, and IEEE Dictionary.

Rel = Reliability calculation based on the exponential distribution. Reference RAC Toolkit, MIL-STD-338, and IEEE Dictionary. λ represents the failure rate of the item and ι represents the period of data collection in calendar time divided by 8760.

Total_Fails = Total number of failure occurrences during the Total Period.

Total_Maint = Total number of maintenance actions (Scheduled Maintenance) during the Total Period.

MTBF = Mean Time Between Failures is the average time calculated between failure occurrences.

MTTR = Mean Time To Repair is the average time to accomplish repairs on an item.

MTTM = Mean Time To Maintain is the average time

Hrdt/Yr. = (Mean Hours Down Time per Year) = Average hours the item is expected to be not functional based on a year.

The attached database identifies reliability and availability numeric for 204 components. Items with 0 failures, reliability statistics are calculated using the Chi Squared 60% confidence interval based on time truncated data. This common approach to data with no failures associated with the data collection time frame is explained in MIL-HDBK-338, section 8.3.2.5.2, Confidence Limits – Exponential Distribution. These items are identified by an asterisk (*) in the database report.

TABLE 1

Calculated Data	Formula for Calculation
Ao, Operational Availability	Ao = (MTBF/MTBF+MDT)
Ai, Inherent Availability	Ai = (MTBF/MTBF+MTTR)
Rel, Reliability	Rel = $e^{-\lambda\tau}$
FR, Failure Rate (per Year)	FR/Yr. = Total Failures/(Tp / 8760)
MTBF, Mean Time Between Failures	MTBF = Tp / Total_Fails
MTTR, Mean Time To Repair	MTTR = Rdt / Total_Fails
MTTM, Mean Time To Maintain	MTTM = Mdt / Total_Maint
MTBM, Mean Time Between Maintenance	MTBM = Tp / All Actions, Maintenance and Repair
MDT, Mean Down Time	MDT = (Rdt + Mdt) / All Actions, Maintenance and Repair
Hours Downtime per Year	Hrdt/Yr. = (rpt_repair_time + rpt_maint_time) / (Tp/8760)

V. CONCLUSIONS

Information collected in this study is useful in determining the site reliability or availability. The actual value that is predicted for a specific system may not be totally definitive, but the comparisons between systems is of greater value.

The data and procedure can be used in different manners to aid the facility designer and facility engineer. The designer can use the data to evaluate different designs. The designer can estimate the length of downtime by adding the failure time to the production or mission loss and can estimate the total length of time from line stop to line start as a result of failures. New designs or redesigns can be evaluated to minimize the production/mission failure with estimates on money saved by avoiding downtime. The engineer can estimate the down times associated with the systems or sub-systems and compare these results to the actual times. This could identify problem areas that may need more (or less) maintenance time and systems that may benefit from redundancy or replacement.

VI. WHERE TO GET ADDITIONAL INFORMATION

Additional information including list of contacts and specific maintenance information may be obtained from:

U.S. Army Corps of Engineers
Special Missions Office
Power Reliability Enhancement Program (PREP)
10115 Gridley Road
Fort Belvoir, VA 22060-5859
(703) 704-2777

Reliability Analysis Center
201 Mill Street
Rome, NY 13440-6916
(315) 337-0900

REFERENCES

[1] GO, available from Electric Power Software Center, University Computing Company, 1930 Hi Line Drive, Dallas, TX 75207.
[2] Design of Reliable Industrial and Commercial Power Systems, IEEE Standard 493-1990.
[3] Dickinson, W.H., Gannon, P.E., Heising, C.R., Patton, A.D., and McWilliams, D.W., "Fundamentals of Reliability Techniques as Applied to Industrial Power Systems," Conference Record 1971, IEEE Industrial Commercial Power Systems Technical Conference, 71C18-IGA, p. 10-31.
[4] Singh, C. and Billinton, R., *System Reliability Modeling and Evaluation*, Hutchinson Educational, London, England, 1977.
[5] IEEE Standard 493-1980, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems, Table 2. In general, failure duration is actual hours downtime per failure based on industry averages. Data from "All Equipment Failures" are used, as opposed to median plant averages, which use data of all plants that reported actual outage time on equipment failures.

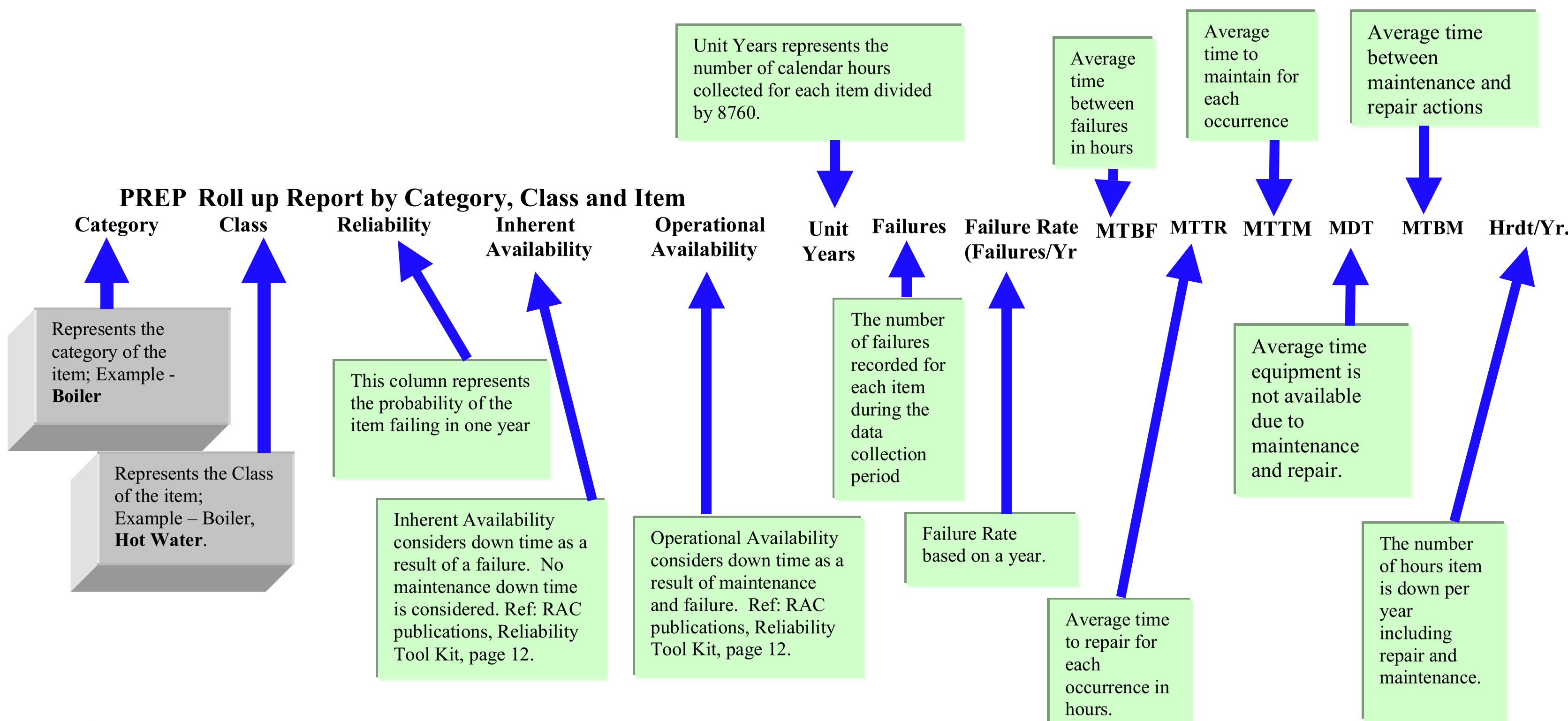
BIOGRAPHIES

Peyton S. Hale, Jr. received his B.S. in Mechanical Engineering, from the University of Virginia in 1983. He received his Masters Degree in Engineering Management from George Washington University in 1993. His principal responsibilities include performing reliability/availability analyses, leading site field surveys and preparing recommended system improvement documents for electrical and mechanical systems for critical Command, Control, Communications and Intelligence (C3I) facilities.

Robert G. Arno received his B.S. in Electrical Engineering from State University of New York at Utica/Rome in 1982 and is currently a member of ASQC, Mohawk Valley Chapter. Mr. Arno has worked in the reliability field for 23 years, joining IIT Research Institute in Rome, NY in 1977. His principal responsibilities include program management, electrical and mechanical system analysis and modeling, and data collection and analysis. He managed the described data collection program.

PREP DATABASE /Version 4.2

The header below represents the header in the database. Each column heading is explained in the text boxes. The formulas, representing the column heading, are contained in the table in Section V above.



*Time Truncated. Chi Squared. 60% Single Side Confidence Interval

PREP ***Roll Up Report by Category, Class and Item***

CATEGORY	*CLASS*	*Reliability*	*Inherent Availability*	*Operational Availability*	*Unit Years*	*Failures*	*Failure Rate (Failures/Year)*	*MTBF*	*MTTR*	*MTTM*	*MDT*	*MTBM*	*Hrdt/ Year*
Accumulator		0.993467721	0.999993849	0.999884828	1373.3	9	0.00655	1336648	8.22	0.8375	0.880	7638	1.0089
Pressurized		0.993913727	0.999992102	0.999841861	982.8	6	0.00610	1434920	11.33	0.8555	0.897	5672	1.3853
Item: 1	Accumulator, Pressurized.	0.993913727	0.999992102	0.999841861	982.8	6	0.00610	1434920	11.33	1.0000	0.897	5672	1.3853
Unpressurized		0.992345933	0.999998246	0.999992983	390.4	3	0.00768	1140104	2.00	0.3333	0.421	60005	0.0615
Item: 2	Accumulator, Unpressurized.	0.992345933	0.999998246	0.999992983	390.4	3	0.00768	1140104	2.00	0.0000	0.421	60005	0.0615
Air Compressor		0.964395571	0.999966392	0.999377084	799.9	29	0.03625	241630.3	8.12	0.3086	0.326	523	5.4567
Electric		0.926805720	0.999919556	0.999207149	315.7	24	0.07601	115246	9.27	0.1602	0.178	224	6.9454
Item: 3	Air Compressor, Electric.	0.926805720	0.999919556	0.999207149	315.7	24	0.07601	115246	9.27	0.0000	0.178	224	6.9454
Fuel		0.989726301	0.999996935	0.999487902	484.2	5	0.01033	848275.2	2.60	2.0028	2.006	3916	4.4860
Item: 4	Air Compressor, Fuel.	0.989726301	0.999996935	0.999487902	484.2	5	0.01033	848275.2	2.60	2.0000	2.006	3916	4.4860
Air Dryer		0.997716217	0.999998695	0.999926162	437.4	1	0.00229	3831360	5.00	0.9326	0.946	12814	0.6468
All Types		0.997716217	0.999998695	0.999926162	437.4	1	0.00229	3831360	5.00	0.9326	0.946	12814	0.6468
Item: 5	Air Dryer, All Types.	0.997716217	0.999998695	0.999926162	437.4	1	0.00229	3831360	5.00	1.0000	0.946	12814	0.6468
Air Handling Unit		0.989056337	0.999997032	0.999875595	1817.5	20	0.01100	796075.2	2.36	xxx	99.036	796075	1.0898
Non-humid wo/Drive		0.989056337	0.999997032	0.999875595	1817.5	20	0.01100	796075.2	2.36	xxx	99.036	796075	1.0898
Item: 6	Air Handling Unit, Non-humid wo/Drive.	0.989056337	0.999997032	0.999875595	1817.5	20	0.01100	796075.2	2.36	0.0000	99.036	796075	1.0898
Arrester		0.998679474	0.999999397	0.999999397	1513.5	2	0.00132	6629340	4.00	xxx	4.000	6629340	0.0053
Lightning		0.998679474	0.999999397	0.999999397	1513.5	2	0.00132	6629340	4.00	xxx	4.000	6629340	0.0053
Item: 134	Arrester, Lightning.	0.998679474	0.999999397	0.999999397	1513.5	2	0.00132	6629340	4.00	0.0000	4.000	6629340	0.0053
Battery		0.993006248	0.999990299	0.999969547	10543.8	74	0.00702	1248161.	12.11	0.1490	0.217	7140	0.2668
Gel Cell-Sealed		0.980061731	0.999995402	0.999967422	2333.7	47	0.02014	434961.3	2.00	0.1318	0.152	4660	0.2854
Item: 10	Battery, Gel Cell-Sealed, Strings.	0.980061731	0.999995402	0.999967422	2333.7	47	0.02014	434961.4	2.00	0.0000	0.152	4660	0.2854

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Lead Acid		0.992563514	0.999972627	0.999968207	3215.3	24	0.00746	1173590.	32.13	0.1463	1.023	32190	0.2785
Item: 11	Battery, Lead Acid, System.	0.992563514	0.999972627	0.999968207	3215.3	24	0.00746	1173590.	32.13	0.0000	1.023	32190	0.2785
Nickel-Cadmium		0.999399558	0.999999292	0.999971403	4994.8	3	0.00060	14584865	10.33	0.1591	0.163	5701	0.2505
Item: 246	Battery, Nickel-Cadmium.	0.999399558	0.999999292	0.999971403	4994.8	3	0.00060	14584865	10.33	0.0000	0.163	5701	0.2505
Blower		0.999825378	1.000000000	0.999960812	2920.3	0	0.00017	50160988	xxx	0.0692	0.069	1765	0.3433
wo/Drive		0.999825378	1.000000000	0.999960812	2920.3	0	0.00017	50160988	xxx	0.0692	0.069	1765	0.3433
Item: 12	Blower, wo/Drive.	0.999825378 *	1.000000000	0.999960812	2920.3	0	0.00017 *	50160988 *	0.00	0.0000	0.069	1765	0.3433
Boiler		0.878642210	0.999360697	0.995132436	1113.0	144	0.12938	67708.83	43.29	3.2844	3.738	768	42.639
Hot Water		0.959008598	0.999985268	0.999501894	358.4	15	0.04186	209292.8	3.08	0.9848	1.005	2018	4.3634
Item: 13	Boiler, Hot Water, Gravity and Circulated.	0.959008598	0.999985268	0.999501894	358.4	15	0.04186	209292.8	3.08	1.0000	1.005	2018	4.3634
Steam		0.842870823	0.999064090	0.993057393	754.6	129	0.17094	51245.58	47.96	3.6062	4.120	593	60.817
Item: 14	Boiler, Steam, High Pressure.	0.928026957	0.999619462	0.991492148	468.6	35	0.07469	117277.7	44.63	3.0000	3.162	372	74.528
Item: 15	Boiler, Steam, Low Pressure.	0.719936234	0.998154400	0.995621239	286.1	94	0.32859	26659.1	49.20	0.0000	116.734	26659	38.357
Bus Duct		0.999696290	1.000000000	1.000000000	1679.0	0	0.00030	28838917	xxx	xxx	xxx	xxx	0.0000
All types		0.999696290	1.000000000	1.000000000	1679.0	0	0.00030	28838917	xxx	xxx	xxx	xxx	0.0000
Item: 16	Bus Duct, All types, (100').	0.999696290 *	1.000000000	1.000000000	1679.0	0	0.00030 *	28838917 *	0.00	0.0000	xxx	xxx	0.0000
Cabinet Heaters		0.999897930	0.999999994	0.999978224	9796.7	1	0.00010	85819128	0.50	1.6476	1.647	75612	0.1908
Forced Air Flow		0.999897930	0.999999994	0.999978224	9796.7	1	0.00010	85819128	0.50	1.6476	1.647	75612	0.1908
Item: 17	Cabinet Heaters, Forced Air Flow, Steam or Hot Water.	0.999897930	0.999999994	0.999978224	9796.7	1	0.00010	85819128	0.50	2.0000	1.647	75612	0.1908
Cable		0.998149212	0.999998818	0.999987869	736301.3	1364	0.00185	4728738.	5.59	4.2595	4.361	359452	0.1063
Above Ground		0.999509398	0.999999527	0.999998357	588927.8	289	0.00049	17851235	8.44	6.8680	7.256	4416958	0.0144
Item: 18	Cable, Above Ground, In Conduit, ≤600V, Per 1000ft.	0.999932074	0.999999938	0.999990264	29442.9	2	0.00007	12895993	8.00	13.0000	13.010	1336372	0.0853
Item: 19	Cable, Above Ground, In Conduit, >600V ≤5kV, Per 1000ft.	0.999463225	0.999999476	0.999998707	523356.6	281	0.00054	16315315	8.56	41.0000	16.109	12458162	0.0113
Item: 20	Cable, Above Ground, No Conduit, ≤600V, Per 1000ft.	0.999879838	0.999999966	0.999999904	33286.3	4	0.00012	72896904	2.50	0.0000	0.078	816772	0.0008
Item: 21	Cable, Above Ground, No Conduit, >600V ≤5kV, Per 1000ft.	0.999244433	0.999999655	0.999999655	2646.0	2	0.00076	11589564	4.00	0.0000	0.032	92717	0.0030

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Item: 22	Cable, Above Ground, Trays, ≤600V, Per 1000ft.	0.968468243 *	1.000000000	1.000000000	15.9	0	0.03204 *	273411.8 *	0.00	0.0000	xxx	xxx	0.0000
Item: 23	Cable, Above Ground, Trays, >600V ≤5kV, Per 1000ft.	0.997171966 *	1.000000000	1.000000000	180.1	0	0.00283 *	3093176. *	0.00	0.0000	xxx	xxx	0.0000
Aerial		0.988381339	0.999997295	0.999997259	37478.5	438	0.01169	749570.9	2.03	xxx	1.907	695576	0.0240
Item: 32	Cable, Aerial, ≤15kV, Per Mile.	0.953928762	0.999990218	0.999990218	6593.7	311	0.04717	185725.9	1.82	0.0000	1.817	185726	0.0857
Item: 33	Cable, Aerial, >15kV, Per Mile.	0.995896395	0.999998806	0.999998762	30884.9	127	0.00411	2130325.	2.54	0.0000	2.081	1680443	0.0108
Below Ground		0.994225869	0.999995527	0.999928197	109482.8	634	0.00579	1512727.	6.77	4.1354	4.238	59023	0.6290
Item: 35	Cable, Below Ground, Duct, ≤600V, Per 1000ft.	0.999875009	0.999999766	0.999999697	40000.4	5	0.00012	70080729	16.40	1.0000	2.789	9221149	0.0026
Item: 36	Cable, Below Ground, Duct, >600V ≤5kV, Per 1000ft.	0.987125021 *	1.000000000	1.000000000	39.4	0	0.01296 *	676000 *	0.00	0.0000	xxx	xxx	0.0000
Item: 47	Cable, Below Ground, In Conduit, ≤600V, Per 1000ft.	0.997994901	0.999997428	0.999991686	24413.2	49	0.00201	4364479.	11.22	88.0000	28.222	3394595	0.0728
Item: 48	Cable, Below Ground, In Conduit >600V ≤5kV, per 1000ft.	0.997646877	0.999995779	0.999987126	19525.5	46	0.00236	3718331	15.70	211.0000	41.547	3227231	0.1128
Item: 46	Cable, Below Ground, Insulated, >5kV, Per 1000ft.	0.980031515	0.999988193	0.999674546	22508.1	454	0.02017	434296.5	5.13	4.0000	4.007	12312	2.8510
Item: 38	Cable, Below Ground, Insulated, ≤600V, Per 1000ft.	0.973653295	0.999976836	0.999976836	2996.3	80	0.02670	328089.9	7.60	0.0000	7.600	328090	0.2029
Insulated		0.992748496	0.999998338	0.999998338	412.2	3	0.00728	1203640	2.00	0.0000	0.109	65653	0.0146
Item: 49	Cable, Insulated, DC, Per 100ft.	0.992748496	0.999998338	0.999998338	412.2	3	0.00728	1203640	2.00	0.0000	0.109	65653	0.0146
Cable Connection		0.999629261	0.999999968	0.999999968	21574.5	8	0.00037	23624073	0.75	xxx	0.750	23624073	0.0003
Item: 29	Cable Connection	0.999629261	0.999999968	0.999999968	21574.5	8	0.00037	23624073	0.75	0.0000	0.750	23624073	0.0003
Capacitor Bank		0.839937440	0.999954142	0.999942075	567.6	99	0.17443	50221.33	2.30	10.0000	2.743	47352	0.5074
Power Factor Corrector		0.839937440	0.999954142	0.999942075	567.6	99	0.17443	50221.33	2.30	10.0000	2.743	47352	0.5074
Item: 54	Capacitor Bank, Power Factor Corrector, (in kVAR).	0.839937440	0.999954142	0.999942075	567.6	99	0.17443	50221.3	2.30	10.0000	2.743	47352	0.5074

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Charger		0.992621004	0.999999577	0.999986472	270.0	2	0.00741	1182768	0.50	0.1297	0.133	9816	0.1185
Battery		0.992621004	0.999999577	0.999986472	270.0	2	0.00741	1182768	0.50	0.1297	0.133	9816	0.1185
Item: 9	Charger, Battery.	0.992621004	0.999999577	0.999986472	270.0	2	0.00741	1182768	0.50	0.0000	0.133	9816	0.1185
Chiller		0.888515818	0.999829779	0.997620632	2021.9	239	0.11820	74109.90	12.62	1.0881	1.164	489	20.843
Absorption		0.841986658	0.999769437	0.995132437	430.3	74	0.17199	50932.86	11.74	0.6240	0.653	134	42.639
Item: 244	Chiller, Absorption.	0.841986658	0.999769437	0.995132437	430.3	74	0.17199	50932.9	11.74	1.0000	0.653	134	42.639
Centrifugal		0.955142622	0.999923928	0.997604888	544.7	25	0.04589	190872.1	14.52	5.2247	5.333	2227	20.981
Item: 55	Chiller, Centrifugal, 600 - 1000 Tons.	0.955142622	0.999923928	0.997604888	544.7	25	0.04589	190872.1	14.52	5.0000	5.333	2227	20.981
Reciprocating		0.864557699	0.999799791	0.998898189	948.2	138	0.14554	60190.78	12.05	1.5457	1.837	1667	9.6519
Item: 56	Chiller, Reciprocating, Closed, w/Drive, 50 - 200 Tons.	0.879941865	0.999809524	0.998734968	680.2	87	0.12790	68491.3	13.05	1.0000	1.662	1314	11.081
Item: 57	Chiller, Reciprocating, Open, wo/Drive, 50 - 200 Tons.	0.826705884	0.999775088	0.999312485	268.0	51	0.19031	46031.1	10.35	3.0000	3.611	5252	6.0226
Rotary		0.986993503	0.999964132	0.996197991	76.4	1	0.01309	669120	24.00	6.0723	6.115	1608	33.305
Item: 58	Chiller, Rotary, 600 - 1000 Tons.	0.986993503	0.999964132	0.996197991	76.4	1	0.01309	669120	24.00	6.0000	6.115	1608	33.305
Screw		0.956286690	0.999510164	0.996566046	22.4	1	0.04470	195984	96.00	1.0000	1.164	339	30.081
Item: 59	Chiller, Screw, >300 Tons.	0.956286690	0.999510164	0.996566046	22.4	1	0.04470	195984	96.00	1.0000	1.164	339	30.081
Circuit Breaker, 600v		0.999996752	0.999999582	0.999983888	157040.9	52	0.00000	26974078	xxx	1.9167	1.959	121569	0.1411
3 Phase, Fixed		0.999996551	0.999999899	0.999992732	147880.0	5	0.00000	25400557	xxx	8.2967	8.376	1152516	0.0637
Item: 61	Circuit Breaker, 600V, 3 Phase, Fixed, Including molded case, ≤600 amp, Normally Closed, Trp. Ckt. Incl.	0.999984307 *	1.000000000	0.999997443	32498.7	0	0.00002 *	55821363 *	0.00	3.0000	3.098	1211442	0.0224
Item: 60	Circuit Breaker, 600V, 3 Phase, Fixed, Including molded case, ≤600 amp, Normally Open, Trp. Ckt. Incl.	0.999887215	0.999999760	0.999990187	26597.8	3	0.00011	77665552	18.67	9.0000	8.727	889300	0.0860
Item: 63	Circuit Breaker, 600V, 3 Phase, Fixed, Including molded case, >600 amp, Normally Closed, Trp. Ckt. Incl.	0.999994218 *	1.000000000	0.999992509	88200.2	0	0.00001 *	15149685 *	0.00	14.0000	13.618	1817962	0.0656
Item: 62	Circuit Breaker, 600V, 3 Phase, Fixed, Including molded case>600V ≤5kV	0.996576534	0.999985320	0.999880051	583.2	2	0.00343	2554428	37.50	3.0000	3.034	25291	1.0507

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Drawout (Metal Clad)		0.998892235	0.999999605	0.999837990	7217.8	8	0.00111	7903437.	3.13	2.0569	2.059	12706	1.4192
Item: 67	Circuit Breaker, 600V, Drawout (Metal Clad), <600 amp, Normally Closed, Trp. Ckt. Incl.	0.999792091	0.999999858	0.999798004	4809.3	1	0.00021	42129480	6.00	2.0000	2.019	9998	1.7695
Item: 66	Circuit Breaker, 600V, Drawout (Metal Clad), <600 amp, Normaly Open, Trp. Ckt. Incl.	0.997456731	0.999998256	0.999860901	785.4	2	0.00255	3440004	6.00	3.0000	2.945	21169	1.2185
Item: 69	Circuit Breaker, 600V, Drawout (Metal Clad), >600 amp, Normally Closed, Trp. Ckt. Incl.	0.998150509	0.999999894	0.999954301	1080.4	2	0.00185	4732057.	0.50	1.0000	1.481	32411	0.4003
Item: 68	Circuit Breaker, 600V, Drawout (Metal Clad), >600 amp, Normally Open, Trp. Ckt. Incl.	0.994487152	0.999998738	0.999927638	542.7	3	0.00553	1584631.	2.00	2.0000	2.372	32785	0.6339
Vacuum		0.980129686	0.999975385	0.999852780	1943.2	39	0.02007	436464	10.74	0.4031	0.480	3263	1.2897
Item: 78	Circuit Breaker, 5kV, Vacuum, <600 amp, Normally Closed, Trp. Ckt. Incl.	0.997191564	0.999997432	0.999960511	355.6	1	0.00281	3114792	8.00	0.0000	0.050	1257	0.3459
Item: 79	Circuit Breaker, 5kV, Vacuum, <600 amp, Normally Open, Trp. Ckt. Incl.	0.998887668 *	1.000000000	0.999983060	458.2	0	0.00111 *	7870964. *	0.00	2.0000	1.838	108492	0.1484
Item: 80	Circuit Breaker, 5kV, Vacuum, >600 amp, Normally Closed, Trp. Ckt. Incl.	0.976752059	0.999960259	0.999619774	425.1	10	0.02352	372410.4	14.80	1.0000	1.620	4261	3.3308
Item: 81	Circuit Breaker, 5kV, Vacuum, >600 amp, Normally Open, Trp. Ckt. Incl.	0.961020019	0.999957368	0.999854272	704.2	28	0.03976	220321.7	9.39	0.0000	0.492	3377	1.2766
Compressor		0.986548811	0.999986587	0.999865676	1255.3	17	0.01354	646853.6	8.68	0.9208	1.011	7527	1.1767
Refrigerant		0.995193627	0.999998075	0.999907183	1037.8	5	0.00482	1818196.	3.50	0.9110	0.925	9968	0.8131
Item: 84	Compressor, Refrigerant, >1 Ton.	0.995193627	0.999998075	0.999907183	1037.8	5	0.00482	1818196.	3.50	1.0000	0.925	9968	0.8131
Screw Type		0.946328222	0.999931777	0.999667651	217.5	12	0.05517	158794	10.83	0.9372	1.154	3471	2.9114
Item: 85	Compressor, Screw Type.	0.946328222	0.999931777	0.999667651	217.5	12	0.05517	158794	10.83	1.0000	1.154	3471	2.9114

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Condensers		0.900083857	0.999913810	0.999583534	1102.0	116	0.10527	83216.68	7.17	4.0979	4.497	10798	3.6482
Double Tube		0.973573588	0.999992357	0.999758971	298.7	8	0.02678	327087	2.50	2.6323	2.628	10903	2.1114
Item: 86	Condensers, Double Tube.	0.973573588	0.999992357	0.999758971	298.7	8	0.02678	327087	2.50	3.0000	2.628	10903	2.1114
Propeller Type Fans/Coils		0.733621551	0.999734138	0.999393134	348.7	108	0.30976	28279.77	7.52	3.0905	4.165	6863	5.3161
Item: 87	Condensers, Propeller Type Fans/Coils, DX.	0.733621551	0.999734138	0.999393134	348.7	108	0.30976	28279.8	7.52	3.0000	4.165	6863	5.3161
Shell and Tube		0.998878743	1.000000000	0.999614286	454.6	0	0.00112	7808282.	xxx	7.3493	7.349	19054	3.3789
Item: 88	Condensers, Shell and Tube.	0.998878743 *	1.000000000	0.999614286	454.6	0	0.00112 *	7808282. *	0.00	7.0000	7.349	19054	3.3789
Control Panel		0.994698171	0.999998908	0.999800824	5643.4	30	0.00532	1647876.	1.80	4.4410	4.406	22119	1.7448
Generator		0.988952766	0.999997330	0.999980962	1710.4	19	0.01111	788570.5	2.11	0.5703	0.635	33369	0.1668
Item: 128	Control Panel, Generator, wo/ Switchgear.	0.988952766	0.999997330	0.999980962	1710.4	19	0.01111	788570.6	2.11	1.0000	0.635	33369	0.1668
HVAC/Chillers/AHUs		0.999848787	1.000000000	0.999982209	3372.5	0	0.00015	57926964	xxx	1.0449	1.045	58733	0.1559
Item: 129	Control Panel, HVAC/Chillers/AHUs, wo/ Switchgear.	0.999848787 *	1.000000000	0.999982209	3372.5	0	0.00015 *	57926964 *	0.00	1.0000	1.045	58733	0.1559
Switchgear controls		0.980568763	0.999997149	0.998160003	560.6	11	0.01962	446426.1	1.27	7.0925	7.043	3828	16.118
Item: 130	Control Panel, Switchgear controls.	0.980568763	0.999997149	0.998160003	560.6	11	0.01962	446426.2	1.27	7.0000	7.043	3828	16.118
Convectors		0.999913016	1.000000000	0.999998481	5862.9	0	0.00009	10070423	xxx	0.0149	0.015	9830	0.0133
Fin Tube Baseboard		0.999913016	1.000000000	0.999998481	5862.9	0	0.00009	10070423	xxx	0.0149	0.015	9830	0.0133
Item: 89	Convectors, Fin Tube Baseboard, Electric.	0.999582861 *	1.000000000	0.999999626	1222.4	0	0.00042 *	20995811 *	0.00	0.0000	0.005	12702	0.0033
Item: 90	Convectors, Fin Tube Baseboard, Steam or Hot Water.	0.999890105 *	1.000000000	0.999998180	4640.6	0	0.00011 *	79708423 *	0.00	0.0000	0.017	9277	0.0159
Cooling Tower		0.968333522	0.999702865	0.997170520	839.1	27	0.03218	272229.7	80.89	1.0681	1.192	421	24.786
Atmospheric Type		0.928543791	0.999247479	0.994184363	323.7	24	0.07414	118158.4	88.92	0.9918	1.137	196	50.945
Item: 94	Cooling Tower, Atmospheric Type, wo/ fans, motors, pumps, valves, etc.	0.928543791	0.999247479	0.994184363	323.7	24	0.07414	118158.5	88.92	1.0000	1.137	196	50.945
Evaporative Type		0.994195540	0.999988924	0.999046330	515.3	3	0.00582	1504800	16.67	1.4429	1.458	1529	8.3542
Item: 95	Cooling Tower, Evaporative Type, wo/ fans, motors, pumps, valves, etc.	0.994195540	0.999988924	0.999046330	515.3	3	0.00582	1504800	16.67	1.0000	1.458	1529	8.3542

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Damper Assembly		0.999971953	0.999999975	0.999990131	18183.5	2	0.00003	31232804	xxx	0.0540	0.054	5486	0.0865
Motor		0.999966919	1.000000000	0.999989337	15416.3	0	0.00003	26479769	xxx	0.0497	0.050	4656	0.0934
Item: 96	Damper Assembly, Motor.	0.999966919 *	1.000000000	0.999989337	15416.3	0	0.00003 *	26479769 *	0.00	0.0000	0.050	4656	0.0934
Pneumatic		0.999277503	0.999999835	0.999994555	2767.2	2	0.00072	12120240	2.00	4.0000	3.882	712955	0.0477
Item: 97	Damper Assembly, Pneumatic.	0.999277503	0.999999835	0.999994555	2767.2	2	0.00072	12120240	2.00	4.0000	3.882	712955	0.0477
Diesel Engine Generator		0.589772164	0.998540049	0.993985981	1354.1	715	0.52802	16590.31	24.22	2.0554	2.642	439	52.682
Packaged		0.775917369	0.999329810	0.997272882	938.1	238	0.25371	34527.71	23.14	1.1483	1.498	549	23.889
Item: 99	Diesel Engine Generator, Packaged, 250kW-1.5MW, Continuous.	0.558396351	0.998287624	0.996927250	266.0	155	0.58269	15033.8	25.74	1.0000	1.149	374	26.917
Item: 98	Diesel Engine Generator, Packaged, 250kW-1.5MW, Standby.	0.883822868	0.999742312	0.997409685	672.1	83	0.12350	70932	18.28	2.0000	1.748	675	22.691
Unpackaged		0.317735957	0.996759289	0.986574653	416.0	477	1.14653	7640.415	24.76	3.2103	4.064	303	117.60
Item: 101	Diesel Engine Generator, Unpackaged, 750kW-7MW, Continuous.	0.162719469	0.994801067	0.980739869	180.6	328	1.81573	4824.5	25.08	4.0000	4.997	259	168.71
Item: 100	Diesel Engine Generator, Unpackaged, 750kW-7MW, Standby.	0.531004159	0.998262059	0.991052357	235.4	149	0.63299	13839.2	24.05	3.0000	3.106	347	78.381
Drive		0.978172315	0.999958316	0.999925947	2990.6	66	0.02207	396929.0	16.55	3.4472	6.218	83966	0.6487
Adjustable Speed		0.978172315	0.999958316	0.999925947	2990.6	66	0.02207	396929.0	16.55	3.4472	6.218	83966	0.6487
Item: 138	Drive, Adjustable Speed.	0.978172315	0.999958316	0.999925947	2990.6	66	0.02207	396929.1	16.55	3.0000	6.218	83966	0.6487
Evaporator		0.995968933	0.999993228	0.999908962	7922.3	32	0.00404	2168739	14.69	0.2565	0.277	3040	0.7975
Coil		0.995812835	0.999992633	0.999899263	6911.4	29	0.00420	2087724.	15.38	0.2689	0.290	2876	0.8825
Item: 82	Evaporator, Coil, Direct Expansion.	0.995812835	0.999992633	0.999899263	6911.4	29	0.00420	2087724.	15.38	0.0000	0.290	2876	0.8825
Shell Tube		0.997036799	0.999997290	0.999975270	1010.9	3	0.00297	2951880	8.00	0.1097	0.123	4972	0.2166
Item: 174	Evaporator, Shell Tube, Direct Expansion.	0.997036799	0.999997290	0.999975270	1010.9	3	0.00297	2951880	8.00	0.0000	0.123	4972	0.2166

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Fan		0.987559807	0.999971610	0.999351118	2396.5	30	0.01252	699780	19.87	4.2211	4.372	6737	5.6842
Centrifugal		0.981021428	0.999946483	0.999770440	782.8	15	0.01916	457179.2	24.47	1.6118	2.061	8976	2.0109
Item: 106	Fan, Centrifugal.	0.981021428	0.999946483	0.999770440	782.8	15	0.01916	457179.2	24.47	2.0000	2.061	8976	2.0109
Propeller/Disc		0.989640193	0.999957798	0.999093547	384.1	4	0.01041	841188	35.50	1.8677	1.954	2156	7.9405
Item: 107	Fan, Propeller/Disc.	0.989640193	0.999957798	0.999093547	384.1	4	0.01041	841188	35.50	2.0000	1.954	2156	7.9405
Tubeaxial		0.989938879	0.999990870	0.999055744	1087.8	11	0.01011	866290.9	7.91	11.4244	11.375	12047	8.2717
Item: 108	Fan, Tubeaxial.	0.989938879	0.999990870	0.999055744	1087.8	11	0.01011	866290.9	7.91	11.0000	11.375	12047	8.2717
Vaneaxial		0.996408668	1.000000000	1.000000000	141.8	0	0.00360	2434823.	xxx	xxx	xxx	xxx	0.0000
Item: 109	Fan, Vaneaxial.	0.996408668 *	1.000000000	1.000000000	141.8	0	0.00360 *	2434823. *	0.00	0.0000	xxx	xxx	0.0000
Filter		0.999898973	1.000000000	0.999903911	5047.9	0	0.00010	86704894	xxx	0.2894	0.289	3012	0.8417
Electrical Tempest		0.998510134	1.000000000	1.000000000	342.1	0	0.00149	5875341.	xxx	0.0000	0.000	2996424	0.0000
Item: 113	Filter, Electrical Tempest.	0.998510134 *	1.000000000	1.000000000	342.1	0	0.00149 *	5875341. *	0.00	0.0000	0.000	2996424	0.0000
Mechanical		0.999891630	1.000000000	0.999896927	4705.8	0	0.00011	80829552	xxx	0.2894	0.289	2808	0.9029
Item: 110	Filter, Mechanical, Air Regulator Set.	0.999840000 *	1.000000000	0.999981949	3187.2	0	0.00016 *	54745647 *	0.00	0.0000	0.044	2464	0.1581
Item: 112	Filter, Mechanical, Fuel Oil.	0.999271146 *	1.000000000	0.999910729	699.5	0	0.00073 *	12014494 *	0.00	0.0000	0.486	5442	0.7820
Item: 111	Filter, Mechanical, Lube Oil.	0.999377566 *	1.000000000	0.999554311	819.1	0	0.00062 *	14069411 *	0.00	1.0000	1.439	3229	3.9042
Fuse		0.997969725	1.000000000	1.000000000	1145.4	0	0.00087	10033704	xxx	xxx	xxx	xxx	0.0000
>5kV ≤ 15kV		0.999341365	1.000000000	1.000000000	774.1	0	0.00066	13295858	xxx	xxx	xxx	xxx	0.0000
Item: 116	Fuse, >5kV ≤15kV.	0.999341365 *	1.000000000	1.000000000	774.1	0	0.00066 *	13295858 *	0.00	0.0000	xxx	xxx	0.0000
0-5kV		0.998627456	1.000000000	1.000000000	371.3	0	0.00137	6377929.	xxx	xxx	xxx	xxx	0.0000
Item: 115	Fuse, 0-5kV.	0.998627456 *	1.000000000	1.000000000	371.3	0	0.00137 *	6377929. *	0.00	0.0000	xxx	xxx	0.0000
Gas Turbine Generator		0.647849145	0.998890863	0.990692798	921.5	400	0.43410	20179.80	22.38	2.1583	2.419	260	81.531
Packaged		0.587787144	0.998689955	0.989043771	750.9	399	0.53139	16485.05	21.60	2.1103	2.366	216	95.976
Item: 119	Gas Turbine Generator, Packaged, 750kW-7MW, Continuous.	0.177710554	0.994598022	0.983584136	167.9	290	1.72760	5070.6	27.39	1.0000	1.225	75	143.80
Item: 118	Gas Turbine Generator, Packaged, 750kW-7MW, Standby.	0.829472916	0.999868149	0.990615770	583.0	109	0.18696	46853.7	6.18	4.0000	4.453	475	82.205

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Unpackaged		0.994155201	0.999775158	0.997950995	170.6	1	0.00586	1494384	336.00	4.5892	5.146	2512	17.949
Item: 121	Gas Turbine Generator, Unpackaged, 750kW-7MW, Continuous.	0.994155201	0.999775158	0.997950995	170.6	1	0.00586	1494384	336.00	5.0000	5.146	2512	17.949
Gauge		0.999042094	1.000000000	0.999999785	532.2	0	0.00096	9140564.	xxx	xxx	xxx	xxx	0.0019
Fluid level		0.999042094	1.000000000	0.999999785	532.2	0	0.00096	9140564.	xxx	xxx	xxx	xxx	0.0019
Item: 122	Gauge, Fluid level.	0.999042094 *	1.000000000	0.999999785	532.2	0	0.00096 *	9140564. *	0.00	0.0000	xxx	xxx	0.0019
Heat Exchanger		0.989034610	0.999997303	0.998935596	634.9	7	0.01103	794489.1	2.14	1.8371	1.838	1727	9.3242
Boiler System		0.971835048	0.999998369	0.997231137	210.0	6	0.02857	306624	0.50	29.2586	28.300	10221	24.255
Item: 123	Heat Exchanger, Boiler System, Steam.	0.971835048	0.999998369	0.997231137	210.0	6	0.02857	306624	0.50	29.0000	28.300	10221	24.255
Lube Oil		0.996596565	0.999995330	0.999740960	293.3	1	0.00341	2569488	12.00	6.5360	6.590	25440	2.2692
Item: 125	Heat Exchanger, Lube Oil.	0.996596565	0.999995330	0.999740960	293.3	1	0.00341	2569488	12.00	7.0000	6.590	25440	2.2692
Water to Water		0.996130029	1.000000000	0.999861134	131.5	0	0.00388	2259200	xxx	0.0544	0.054	392	1.2165
Item: 124	Heat Exchanger, Water to Water.	0.996130029 *	1.000000000	0.999861134	131.5	0	0.00388 *	2259200 *	0.00	0.0000	0.054	392	1.2165
Heater		0.947826981	0.999984168	0.994164558	317.3	17	0.05358	163483.7	2.59	1.2053	1.207	207	51.118
Electric		0.947826981	0.999984168	0.994164558	317.3	17	0.05358	163483.7	2.59	1.2053	1.207	207	51.118
Item: 126	Heater, Electric, Lube/Fuel Oil or Jacket.	0.947826981	0.999984168	0.994164558	317.3	17	0.05358	163483.8	2.59	1.0000	1.207	207	51.118
Humistat		0.984575905	0.999998226	0.999998226	643.3	10	0.01554	563551.2	1.00	0.0000	0.043	24083	0.0155
Assembly		0.984575905	0.999998226	0.999998226	643.3	10	0.01554	563551.2	1.00	0.0000	0.043	24083	0.0155
Item: 127	Humistat, Assembly.	0.984575905	0.999998226	0.999998226	643.3	10	0.01554	563551.2	1.00	0.0000	0.043	24083	0.0155
Inverters		0.995190512	0.999985691	0.999598793	414.8	2	0.00482	1817016	26.00	5.1691	5.321	13263	3.5146
All Types		0.995190512	0.999985691	0.999598793	414.8	2	0.00482	1817016	26.00	5.1691	5.321	13263	3.5146
Item: 131	Inverters, All Types.	0.995190512	0.999985691	0.999598793	414.8	2	0.00482	1817016	26.00	5.0000	5.321	13263	3.5146
Meter		0.998913484	0.999993988	0.999993961	16557.7	18	0.00109	8058086.	48.44	0.0055	1.182	195743	0.0529
Electric		0.999635167	0.999999958	0.999999958	13702.4	5	0.00036	24006614	1.00	0.0000	0.025	606228	0.0004
Item: 135	Meter, Electric.	0.999635167	0.999999958	0.999999958	13702.4	5	0.00036	24006614	1.00	0.0000	0.025	606228	0.0004

CATEGORY	*CLASS*	*Reliability*	*Inherent Availability*	*Operational Availability*	*Unit Years*	*Failures*	*Failure Rate (Failures/Year)*	*MTBF*	*MTTR*	*MTTM*	*MDT*	*MTBM*	*Hrdt/ Year*
Fuel		0.946014073	0.999543853	0.999543853	216.2	12	0.05550	157844	72.00	xxx	72.000	157844	3.9958
Item: 136	Meter, Fuel.	0.946014073	0.999543853	0.999543853	216.2	12	0.05550	157844	72.00	0.0000	72.000	157844	3.9958
Water		0.999621152	0.999999870	0.999999697	2639.1	1	0.00038	23118360	3.00	0.0075	0.013	43537	0.0027
Item: 137	Meter, Water.	0.999621152	0.999999870	0.999999697	2639.1	1	0.00038	23118360	3.00	0.0000	0.013	43537	0.0027
Motor Generator Set		0.975052652	0.999978501	0.993070544	435.4	11	0.02526	346741.0	7.45	0.8368	0.839	121	60.702
3 Phase, 400HZ		0.995075131	0.999995491	0.999628032	202.6	1	0.00494	1774344	8.00	2.8722	2.895	7782	3.2584
Item: 144	Motor Generator Set, 3 Phase, 400HZ.	0.995075131	0.999995491	0.999628032	202.6	1	0.00494	1774344	8.00	3.0000	2.895	7782	3.2584
3 Phase, 60HZ		0.957963867	0.999963722	0.987366458	232.9	10	0.04295	203980.8	7.40	0.8220	0.824	65	110.66
Item: 147	Motor Generator Set, 3 Phase, 60HZ.	0.957963867	0.999963722	0.987366458	232.9	10	0.04295	203980.8	7.40	1.0000	0.824	65	110.66
Motor Starter		0.999147052	0.999995416	0.999944527	597.7	1	0.00085	10265882	xxx	0.2442	0.266	4795	0.4859
≤600V		0.998167781	1.000000000	0.999984223	278.1	0	0.00183	4776705.	xxx	0.0814	0.081	5161	0.1382
Item: 150	Motor Starter, ≤600V.	0.998167781 *	1.000000000	0.999984223	278.1	0	0.00183 *	4776705. *	0.00	0.0000	0.081	5161	0.1382
>600V		0.996875738	0.999991427	0.999909983	319.6	1	0.00313	2799480	24.00	0.3683	0.406	4515	0.7885
Item: 151	Motor Starter, >600V.	0.996875738	0.999991427	0.999909983	319.6	1	0.00313	2799480	24.00	0.0000	0.406	4515	0.7885
Motor, Electric		0.999032041	0.999973300	0.999930849	27880.2	27	0.00097	9045589.	241.52	0.5662	0.921	13318	0.6058
DC		0.985531708	0.999031729	0.998182336	754.8	11	0.01457	601071.2	582.00	0.4228	0.904	497	15.922
Item: 141	Motor, Electric, DC.	0.985531708	0.999031729	0.998182336	754.8	11	0.01457	601071.3	582.00	0.0000	0.904	497	15.922
Induction		0.981918899	0.999992950	0.999724259	712.5	13	0.01825	480090.4	3.38	2.9576	2.967	10761	2.4155
Item: 148	Motor, Electric, Induction, ≤600V.	0.988992708	0.999998736	0.999957372	361.4	4	0.01107	791448	1.00	1.0000	1.336	31344	0.3734
Item: 149	Motor, Electric, Induction, >600V.	0.974689985	0.999986993	0.999484292	351.1	9	0.02564	341709.3	4.44	3.0000	3.311	6420	4.5176
Single Phase		0.999980411	0.999999987	0.999988267	26034.5	1	0.00002	44718136	xxx	0.6247	0.625	53286	0.1028
Item: 139	Motor, Electric, Single Phase, ≤5 amp.	0.999979878 *	1.000000000	0.999996192	25345.3	0	0.00002 *	43534240 *	0.00	0.0000	0.491	128934	0.0334
Item: 140	Motor, Electric, Single Phase, >5 amp.	0.998550210	0.999999503	0.999696847	689.3	1	0.00145	6037872	3.00	1.0000	0.716	2360	2.6556

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Synchronous		0.998653401	0.999978284	0.999857033	378.5	2	0.00135	6500894.	xxx	2.2088	2.576	18019	1.2524
Item: 152	Motor, Electric, Synchronous, ≤600V.	0.996555656 *	1.000000000	0.999777580	147.8	0	0.00345 *	2538917. *	0.00	2.0000	2.000	8992	1.9484
Item: 153	Motor, Electric, Synchronous, >600V.	0.991366824	0.999964367	0.999907948	230.7	2	0.00867	1010304	36.00	3.0000	4.650	50515	0.8064
Motor, Mechanical		0.195448823	0.999809717	0.998810724	1154.7	1885	1.63246	5366.145	1.02	2.8441	2.212	1860	10.418
Diesel		0.904562026	0.999953538	0.991433654	129.6	13	0.10030	87334.15	4.06	3.2492	3.253	380	75.041
Item: 142	Motor, Mechanical, Diesel.	0.904562026	0.999953538	0.991433654	129.6	13	0.10030	87334.2	4.06	3.0000	3.253	380	75.041
Gas		0.161029030	0.999791533	0.999743425	1025.1	1872	1.82617	4796.923	1.00	0.7500	0.941	3668	2.2476
Item: 143	Motor, Mechanical, Gas.	0.161029030	0.999791533	0.999743425	1025.1	1872	1.82617	4796.9	1.00	1.0000	0.941	3668	2.2476
Pipe		0.981888041	0.999994337	0.999991952	383.0	7	0.01828	479265	2.71	4.0000	3.000	372762	0.0705
Flex		0.981888041	0.999994337	0.999991952	383.0	7	0.01828	479265	2.71	4.0000	3.000	372762	0.0705
Item: 51	Pipe, Flex, Non-Reinforced, >4".	0.985560776	0.999994466	0.999990038	206.3	3	0.01454	602290.2	3.33	4.0000	3.600	361374	0.0873
Item: 53	Pipe, Flex, Reinforced, >4".	0.977618384	0.999994186	0.999994186	176.7	4	0.02264	386996.1	2.25	0.0000	2.250	386996	0.0509
Piping		0.999960899	0.999998770	0.999676366	13042.9	12	0.00004	22403087	xxx	7.7177	7.728	23878	2.8350
Refrigerant		0.999954550	0.999999430	0.999990919	11221.0	6	0.00005	19273661	xxx	3.0645	3.199	352314	0.0795
Item: 91	Piping, Refrigerant, <1 inch.	0.999925556 *	1.000000000	0.999993884	6850.6	0	0.00007 *	11766837 *	0.00	4.0000	3.670	600109	0.0536
Item: 158	Piping, Refrigerant, <2 inch.	0.997181886	0.999996564	0.999986684	1063.0	3	0.00282	3104080	10.67	1.0000	0.932	70017	0.1166
Item: 159	Piping, Refrigerant, >2 inch.	0.999822269 *	1.000000000	1.000000000	2869.2	0	0.00018 *	49283482 *	0.00	0.0000	xxx	xxx	0.0000
Item: 92	Piping, Refrigerant, 1-3 inch.	0.993176045	0.999993747	0.999895362	438.1	3	0.00685	1279328	8.00	9.0000	8.730	83434	0.9166
Water		0.999720116	0.999994706	0.997739077	1821.9	6	0.00028	31294258	xxx	xxx	8.008	3542	19.805
Item: 154	Piping, Water, ≤2 inch.	0.998834378 *	1.000000000	1.000000000	437.3	0	0.00117 *	7510917. *	0.00	0.0000	xxx	xxx	0.0000
Item: 93	Piping, Water, >12".	0.939385452 *	1.000000000	1.000000000	8.2	0	0.06253 *	140094.1 *	0.00	0.0000	xxx	xxx	0.0000
Item: 155	Piping, Water, >2≤4 inch.	0.979679275	0.999966994	0.999966994	292.3	6	0.02053	426692	14.08	0.0000	14.083	426692	0.2891
Item: 156	Piping, Water, >4≤8 inch.	0.998103531 *	1.000000000	1.000000000	268.7	0	0.00190 *	4614729. *	0.00	0.0000	xxx	xxx	0.0000
Item: 157	Piping, Water, >8≤12 inch.	0.999374866 *	1.000000000	0.994961083	815.6	0	0.00063 *	14008611 *	0.00	8.0000	8.000	1588	44.140

CATEGORY	*CLASS*	*Reliability*	*Inherent Availability*	*Operational Availability*	*Unit Years*	*Failures*	*Failure Rate (Failures/Year)*	*MTBF*	*MTTR*	*MTTM*	*MDT*	*MTBM*	*Hrdt/ Year*
Pressure Control		0.993091820	0.999995568	0.999938101	721.3	5	0.00693	1263676.	5.60	3.3935	3.492	56414	0.5422
Assembly		0.993091820	0.999995568	0.999938101	721.3	5	0.00693	1263676.	5.60	3.3935	3.492	56414	0.5422
Item: 160	Pressure Control, Assembly.	0.993091820	0.999995568	0.999938101	721.3	5	0.00693	1263676.	5.60	3.0000	3.492	56414	0.5422
Pressure Regulator		0.999163441	1.000000000	0.999993069	609.4	0	0.00084	10467090	xxx	0.5000	0.500	72138	0.0607
Hot Gas		0.999163441	1.000000000	0.999993069	609.4	0	0.00084	10467090	xxx	0.5000	0.500	72138	0.0607
Item: 161	Pressure Regulator, Hot Gas.	0.999163441 *	1.000000000	0.999993069	609.4	0	0.00084 *	10467090 *	0.00	0.0000	0.500	72138	0.0607
Pump		0.993705867	0.999994889	0.999826613	1742.2	11	0.00631	1387387.	7.09	0.4204	0.432	2494	1.5189
Centrifugal		0.994206434	0.999995523	0.999903450	1376.8	8	0.00581	1507638	6.75	0.3372	0.353	3654	0.8458
Item: 163	Pump, Centrifugal, Integral Drive.	0.992515450	0.999993654	0.999897429	665.5	5	0.00751	1166025.	7.40	1.0000	0.599	5836	0.8985
Item: 164	Pump, Centrifugal, wo/Drive.	0.995791244	0.999997272	0.999909083	711.3	3	0.00422	2076992	5.67	0.0000	0.246	2707	0.7964
Positive Displacement		0.991821538	0.999992500	0.999537023	365.3	3	0.00821	1066720	8.00	0.5176	0.526	1135	4.0557
Item: 165	Pump, Positive Displacement.	0.991821538	0.999992500	0.999537023	365.3	3	0.00821	1066720	8.00	1.0000	0.526	1135	4.0557
Radiators		0.987545587	0.999977760	0.999934189	877.7	11	0.01253	698976	15.55	0.0999	0.150	2285	0.5765
Small Tube		0.987545587	0.999977760	0.999934189	877.7	11	0.01253	698976	15.55	0.0999	0.150	2285	0.5765
Item: 166	Radiators, Small Tube.	0.987545587	0.999977760	0.999934189	877.7	11	0.01253	698976	15.55	0.0000	0.150	2285	0.5765
Rectifiers		0.995540658	0.999991837	0.998972976	447.5	2	0.00447	1960032	16.00	3.4491	3.471	3379	8.9967
All Types		0.995540658	0.999991837	0.998972976	447.5	2	0.00447	1960032	16.00	3.4491	3.471	3379	8.9967
Item: 168	Rectifiers, All Types.	0.995540658	0.999991837	0.998972976	447.5	2	0.00447	1960032	16.00	3.0000	3.471	3379	8.9967
Sending Unit		0.999566658	0.999999536	0.999999258	36914.4	16	0.00043	20210622	9.38	0.0170	0.045	60956	0.0065
Air Velocity		0.998867884	0.999998707	0.999997599	6179.6	7	0.00113	7733345.	10.00	0.0156	0.034	14050	0.0210
Item: 173	Sending Unit, Air Velocity.	0.998867884	0.999998707	0.999997599	6179.6	7	0.00113	7733345.	10.00	0.0000	0.034	14050	0.0210
Pressure		0.997916028	0.999997883	0.999997089	4314.2	9	0.00209	4199130.	8.89	0.0208	0.076	26028	0.0255
Item: 171	Sending Unit, Pressure.	0.997916028	0.999997883	0.999997089	4314.2	9	0.00209	4199130.	8.89	0.0000	0.076	26028	0.0255
Temperature		0.999980697	1.000000000	1.000000000	26420.6	0	0.00002	45381247	xxx	xxx	xxx	xxx	0.0000
Item: 172	Sending Unit, Temperature.	0.999980697 *	1.000000000	1.000000000	26420.6	0	0.00002 *	45381247 *	0.00	0.0000	xxx	xxx	0.0000
Software Con. ADAS Sys.		0.642221250	0.999854564	0.999658784	551.0	244	0.44282	19782.19	2.88	0.5615	0.855	2505	2.9891
≤1000 Acquistion Points		0.777690112	0.999954199	0.999888246	373.9	94	0.25143	34841.10	1.60	1.2558	1.376	12312	0.9790
Item: 169	Software Con. ADAS Sys., ≤1000 Acquistion Points.	0.777690112	0.999954199	0.999888246	373.9	94	0.25143	34841.1	1.60	1.0000	1.376	12312	0.9790

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
>1000 Acquistion Points		0.428800729	0.999644282	0.999174503	177.1	150	0.84676	10345.28	3.68	0.4825	0.771	934	7.2314
Item: 170	Software Con. ADAS Sys., >1000 Acquistion Points.	0.428800729	0.999644282	0.999174503	177.1	150	0.84676	10345.3	3.68	0.0000	0.771	934	7.2314
Strainer		0.999943310	1.000000000	0.999916767	8996.1	0	0.00006	15452150	xxx	0.3084	0.308	3705	0.7291
Coolant		0.998861684	1.000000000	0.999333463	447.8	0	0.00114	7691200	xxx	1.6290	1.629	2444	5.8389
Item: 177	Strainer, Coolant.	0.998861684 *	1.000000000	0.999333463	447.8	0	0.00114 *	7691200 *	0.00	2.0000	1.629	2444	5.8389
Duplex Fuel/Lube Oil		0.995679886	1.000000000	0.999861421	117.8	0	0.00433	2023341.	xxx	0.8614	0.861	6216	1.2140
Item: 180	Strainer, Duplex Fuel/Lube Oil.	0.995679886 *	1.000000000	0.999861421	117.8	0	0.00433 *	2023341. *	0.00	1.0000	0.861	6216	1.2140
Fuel Oil		0.998766615	1.000000000	0.999924447	413.2	0	0.00123	7098023.	xxx	1.7094	1.709	22625	0.6618
Item: 179	Strainer, Fuel Oil.	0.998766615 *	1.000000000	0.999924447	413.2	0	0.00123 *	7098023. *	0.00	2.0000	1.709	22625	0.6618
Lube Oil		0.999529759	1.000000000	0.999881981	1084.3	0	0.00047	18624376	xxx	1.7380	1.738	14726	1.0339
Item: 178	Strainer, Lube Oil.	0.999529759 *	1.000000000	0.999881981	1084.3	0	0.00047 *	18624376 *	0.00	2.0000	1.738	14726	1.0339
Water		0.999926442	1.000000000	0.999960363	6933.0	0	0.00007	11908456	xxx	0.1288	0.129	3249	0.3472
Item: 175	Strainer, Water, ≤4 inch.	0.999920044 *	1.000000000	0.999999893	6378.3	0	0.00008 *	10955614 *	0.00	0.0000	0.000	3116	0.0009
Item: 176	Strainer, Water, >4 inch.	0.999081068 *	1.000000000	0.999505864	554.7	0	0.00092 *	9528423. *	0.00	3.0000	3.168	6411	4.3286
Switch		0.993744427	0.999996988	0.999960651	9720.8	61	0.00628	1395966.	4.20	1.5333	1.612	40959	0.3447
Automatic Transfer		0.950118163	0.999976051	0.999857315	1074.9	55	0.05117	171197.6	4.10	7.3553	6.490	45487	1.2499
Item: 183	Switch, Automatic Transfer, >600 amp., ≤600V.	0.968631015	0.999994046	0.999809981	690.3	22	0.03187	274853.5	1.64	34.0000	20.891	109941	1.6646
Item: 182	Switch, Automatic Transfer, 0-600 amp., ≤600V.	0.917774618	0.999943753	0.999942269	384.6	33	0.08580	102093.8	5.74	0.0000	1.280	22165	0.5057
Disconnect		0.999846881	0.999999966	0.999961037	3330.5	1	0.00015	57205889	xxx	1.5473	1.547	39694	0.3413
Item: 185	Switch, Disconnect, Enclosed, ≤600V.	0.999394569 *	1.000000000	0.999938186	842.1	0	0.00061 *	14464658 *	0.00	2.0000	1.991	32214	0.5415
Item: 187	Switch, Disconnect, Enclosed, >5kV.	0.998257804	0.999999801	0.999939288	573.5	1	0.00174	5023755.	1.00	2.0000	1.510	24870	0.5318
Item: 186	Switch, Disconnect, Enclosed, >600V ≤5kV.	0.997942528 *	1.000000000	0.999867230	247.6	0	0.00206 *	4253270. *	0.00	2.0000	2.400	18076	1.1631
Item: 65	Switch, Disconnect, Fused, DC, >600 amp., ≤600V.	0.999408178 *	1.000000000	1.000000000	861.5	0	0.00059 *	14797364 *	0.00	0.0000	0.000	314444	0.0000
Item: 64	Switch, Disconnect, Fused, DC, 0-600 amp., ≤600V.	0.999367257 *	1.000000000	0.999987568	805.8	0	0.00063 *	13840094 *	0.00	1.0000	0.548	44115	0.1089

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Electric		0.999358198	0.999999927	0.999999780	3115.2	2	0.00064	13644684	1.00	0.0093	0.014	63170	0.0019
Item: 184	Switch, Electric, On/Off Breaker Type, Non-knife., ≤600V.	0.999358198	0.999999927	0.999999780	3115.2	2	0.00064	13644684	1.00	0.0000	0.014	63170	0.0019
Float		0.997716932	0.999999478	0.999985388	437.5	1	0.00229	3832560	2.00	0.1869	0.193	13216	0.1280
Item: 104	Switch, Float, Electric.	0.997716932	0.999999478	0.999985388	437.5	1	0.00229	3832560	2.00	0.0000	0.193	13216	0.1280
Manual Transfer		0.999129111	1.000000000	0.999966262	585.4	0	0.00087	10054305	xxx	1.4786	1.479	43826	0.2955
Item: 188	Switch, Manual Transfer, ≤600 amp., ≤600V.	0.997919138 *	1.000000000	0.999952908	244.8	0	0.00208 *	4205411. *	0.00	1.0000	1.098	23313	0.4125
Item: 189	Switch, Manual Transfer, >600 amp., ≤600V.	0.998503402 *	1.000000000	0.999975863	340.5	0	0.00150 *	5848894. *	0.00	3.0000	2.880	119317	0.2114
Oil Filled		0.998241979	1.000000000	0.999996849	289.8	0	0.00176	4978494.	xxx	8.0000	8.000	2539032	0.0276
Item: 190	Switch, Oil Filled, ≤5kV.	0.998241979 *	1.000000000	0.999996849	289.8	0	0.00176 *	4978494. *	0.00	8.0000	8.000	2539032	0.0276
Static		0.997748999	0.999996656	0.999919287	887.5	2	0.00225	3887220	13.00	2.0390	2.113	26177	0.7070
Item: 212	Switch, Static, >1000 amp., ≤600V.	0.996326697	0.999989918	0.999739539	271.7	1	0.00368	2380392	24.00	3.0000	3.584	13759	2.2816
Item: 211	Switch, Static, >600 ≤1000 amp., ≤600V.	0.992336720	0.999998244	0.999994731	130.0	1	0.00769	1138728	2.00	0.0000	0.078	14789	0.0462
Item: 210	Switch, Static, 0-600 amp. ≤600V.	0.998950665 *	1.000000000	0.999999648	485.8	0	0.00105 *	8343764. *	0.00	0.0000	0.032	90539	0.0031
Switchgear		0.991916417	0.999974462	0.999585725	4558.7	37	0.00812	1079291.	27.56	3.4490	3.646	8800	3.6291
Bare Bus		0.989863408	0.999968286	0.999579123	3239.0	33	0.01019	859808.3	27.27	3.7329	3.993	9486	3.6869
Item: 191	Switchgear, Bare Bus, ≤600V, All Cabinets,Ckt. Bkrs. Not Included.	0.990554799	0.999992098	0.999455269	1791.3	17	0.00949	923068.2	7.29	4.0000	4.308	7909	4.7718
Item: 193	Switchgear, Bare Bus, >5kV, All Cabinets,Ckt. Bkrs. Not Included.	0.982216877	0.999995342	0.999839597	780.2	14	0.01794	488208.8	2.27	1.0000	1.296	8079	1.4051
Item: 192	Switchgear, Bare Bus, >600V ≤5kV, All Cabinets,Ckt. Bkrs. Not Included.	0.997007868	0.999872746	0.999607036	667.4	2	0.00300	2923296	372.00	10.0000	14.270	36314	3.4424
Insulated Bus		0.999613608	0.999989619	0.999601929	1319.6	4	0.00039	22666917	xxx	2.9046	2.975	7473	3.4871
Item: 194	Switchgear, Insulated Bus, ≤600V, All Cabinets,Ckt. Bkrs. Not Included.	0.998420947 *	1.000000000	0.999468794	322.7	0	0.00158 *	5543247. *	0.00	3.0000	3.182	5990	4.6534

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Item: 196	Switchgear, Insulated Bus, >5kV, All Cabinets,Ckt. Bkrs. Not Included.	0.995913049	0.999982547	0.999626621	732.5	3	0.00410	2139024	37.33	14.0000	14.434	38657	3.2708
Item: 195	Switchgear, Insulated Bus, >600V ≤5kV, All Cabinets,Ckt. Bkrs. Not Included.	0.996224761	0.999996546	0.999696028	264.4	1	0.00378	2316000	8.00	1.0000	0.774	2548	2.6628
Tank		0.995965564	0.999991636	0.999971186	1978.9	8	0.00404	2166924	18.13	0.1221	0.172	5955	0.2524
Day		0.994810377	0.999997030	0.999974756	384.4	2	0.00520	1683600	5.00	0.3074	0.346	13688	0.2211
Item: 198	Tank, Day, Genset Fuel.	0.994810377	0.999997030	0.999974756	384.4	2	0.00520	1683600	5.00	0.0000	0.346	13688	0.2211
Fuel		0.993549151	0.999955673	0.999872929	309.0	2	0.00647	1353576	60.00	1.2584	1.911	15040	1.1131
Item: 197	Tank, Fuel.	0.993549151	0.999955673	0.999872929	309.0	2	0.00647	1353576	60.00	1.0000	1.911	15040	1.1131
Receiver		0.997280535	0.999997824	0.999996891	734.4	2	0.00272	3216840	7.00	0.0029	0.010	3078	0.0272
Item: 167	Tank, Receiver, Air.	0.997280535	0.999997824	0.999996891	734.4	2	0.00272	3216840	7.00	0.0000	0.010	3078	0.0272
Water		0.996377265	0.999999793	0.999989539	551.1	2	0.00363	2413680	0.50	0.1260	0.128	12221	0.0916
Item: 199	Tank, Water.	0.996377265	0.999999793	0.999989539	551.1	2	0.00363	2413680	0.50	0.0000	0.128	12221	0.0916
Thermostat		0.998319168	0.999999398	0.999997565	6538.9	11	0.00168	5207323.	3.14	0.7895	0.969	397782	0.0213
Radiator		0.998319168	0.999999398	0.999997565	6538.9	11	0.00168	5207323.	3.14	0.7895	0.969	397782	0.0213
Item: 201	Thermostat, Radiator.	0.998319168	0.999999398	0.999997565	6538.9	11	0.00168	5207323.	3.14	1.0000	0.969	397782	0.0213
Transducer		0.999978470	0.999999933	0.999998552	23687.4	42	0.00002	40686583	xxx	0.0183	0.019	13235	0.0127
Flow		0.996713345	1.000000000	0.999986736	154.9	0	0.00329	2660941.	xxx	0.3600	0.360	27142	0.1162
Item: 114	Transducer, Flow.	0.996713345 *	1.000000000	0.999986736	154.9	0	0.00329 *	2660941. *	0.00	0.0000	0.360	27142	0.1162
Pressure		0.997477750	0.999999423	0.999987243	791.9	2	0.00253	3468708	2.00	0.6983	0.720	56402	0.1118
Item: 162	Transducer, Pressure.	0.997477750	0.999999423	0.999987243	791.9	2	0.00253	3468708	2.00	1.0000	0.720	56402	0.1118
Temperature		0.998242572	0.999999950	0.999999026	22740.5	40	0.00176	4980177	0.25	0.0119	0.013	12848	0.0085
Item: 200	Transducer, Temperature.	0.998242572	0.999999950	0.999999026	22740.5	40	0.00176	4980177	0.25	0.0000	0.013	12848	0.0085
Transformer, Dry		0.999953743	0.999995817	0.999971899	11025.1	19	0.00005	18937280	xxx	3.2263	3.693	131402	0.2462
Air Cooled		0.999882198	1.000000000	0.999944571	4329.0	0	0.00012	74357512	xxx	4.2724	4.272	77078	0.4856
Item: 202	Transformer, Dry, Air Cooled, ≤500kVA.	0.999775100 *	1.000000000	0.999995570	2267.4	0	0.00022 *	38946258 *	0.00	4.0000	3.826	863591	0.0388

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Item: 204	Transformer, Dry, Air Cooled, >1500kVA ≤3000kVA.	0.999393210 *	1.000000000	0.999745124	840.2	0	0.00061 *	14432242 *	0.00	4.0000	4.206	16503	2.2327
Item: 203	Transformer, Dry, Air Cooled, >500kVA ≤1500kVA.	0.999582527 *	1.000000000	0.999987102	1221.4	0	0.00042 *	20979011 *	0.00	6.0000	6.000	465187	0.1130
Isolation		0.997166548	0.999993113	0.999989567	6696.1	19	0.00284	3087252.	21.26	0.9286	2.519	241390	0.0914
Item: 132	Transformer, Dry, Isolation, Delta Wye, <600V.	0.997166548	0.999993113	0.999989567	6696.1	19	0.00284	3087252.	21.26	1.0000	2.519	241390	0.0914
Transformer, Liquid		0.994797669	0.999950735	0.998990580	8819.2	46	0.00522	1679476.	82.74	16.9047	17.588	17424	8.8425
Forced Air		0.989259891	0.999836759	0.996601877	2593.0	28	0.01080	811246.2	132.43	21.1758	22.066	6494	29.767
Item: 206	Transformer, Liquid, Forced Air, ≤10,000kVA.	0.992879584	0.999797696	0.990915913	419.8	3	0.00715	1225880	248.00	23.0000	23.677	2606	79.576
Item: 205	Transformer, Liquid, Forced Air, ≤5,000kVA.	0.987452327	0.999994736	0.999987215	1821.5	23	0.01263	693748.2	3.65	1.0000	0.976	76345	0.1120
Item: 207	Transformer, Liquid, Forced Air, >10,000kVA ≤50,000kVA.	0.994329760	0.999065253	0.985856760	351.7	2	0.00569	1540524	1440.0	22.0000	23.203	1641	123.89
Non-Forced Air		0.997113141	0.999998203	0.999985412	6226.1	18	0.00289	3030057.	5.44	0.7600	0.850	58270	0.1278
Item: 208	Transformer, Liquid, Non-Forced Air, ≤3000kVA.	0.998891114	0.999999367	0.999996102	5407.8	6	0.00111	7895436	5.00	10.0000	8.394	2153301	0.0341
Item: 241	Transformer, Liquid, Non-Forced Air, >10000kVA ≤50000kVA.	0.982624792	0.999987813	0.999893406	627.6	11	0.01753	499773.8	6.09	1.0000	0.648	6081	0.9338
Item: 209	Transformer, Liquid, Non-Forced Air, >3000kVA ≤10000kVA.	0.994771048	0.999999402	0.999985038	190.7	1	0.00524	1670904	1.00	3.0000	2.500	167090	0.1311
UPS		0.999078297	0.999998349	0.999951289	553.1	4	0.00092	9499764.	xxx	3.8000	3.688	75701	0.4267
Rotary		0.995983397	1.000000000	0.999895500	126.7	0	0.00402	2176564.	xxx	6.1053	6.105	58424	0.9154
Item: 213	UPS, Rotary.	0.995983397 *	1.000000000	0.999895500	126.7	0	0.00402 *	2176564. *	0.00	6.0000	6.105	58424	0.9154
Small Computer Room Floor		0.990661925	0.999997858	0.999967870	426.4	4	0.00938	933708	2.00	2.7317	2.667	82996	0.2815
Item: 216	UPS, Small Computer Room Floor.	0.990661925	0.999997858	0.999967870	426.4	4	0.00938	933708	2.00	3.0000	2.667	82996	0.2815

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Valve		0.999995192	0.999999568	0.999977752	106073.6	183	0.00000	18219692	xxx	0.7962	0.806	36233	0.1949
3-way		0.999727982	1.000000000	0.999987577	1874.6	0	0.00027	32199388	xxx	0.5165	0.516	41574	0.1088
Item: 236	Valve, 3-way, Diverting/Sequencing.	0.999257278 *	1.000000000	0.999999501	686.4	0	0.00074 *	11790070 *	0.00	0.0000	0.015	30368	0.0044
Item: 237	Valve, 3-way, Mixing Control.	0.999570876 *	1.000000000	0.999980689	1188.2	0	0.00043 *	20409317 *	0.00	1.0000	1.020	52836	0.1692
Ball		0.999807822	0.999999957	0.999999204	2653.5	2	0.00019	45578400	xxx	0.1577	0.164	205708	0.0070
Item: 217	Valve, Ball, N.C.	0.999516658 *	1.000000000	0.999998106	1054.9	0	0.00048 *	18119435 *	0.00	0.0000	0.192	101548	0.0166
Item: 218	Valve, Ball, N.O.	0.998749718	0.999999929	0.999999929	1598.6	2	0.00125	7002036	0.50	0.0000	0.045	636549	0.0006
Butterfly		0.998692271	0.999999513	0.999995506	17576.2	23	0.00131	6694253.	3.26	0.5539	0.609	135416	0.0394
Item: 219	Valve, Butterfly, N.C.	0.991788585	0.999996931	0.999990199	2789.5	23	0.00825	1062421.	3.26	1.0000	1.288	131375	0.0859
Item: 220	Valve, Butterfly, N.O.	0.999965510 *	1.000000000	0.999996507	14786.8	0	0.00003 *	25398456 *	0.00	0.0000	0.476	136206	0.0306
Check		0.999742108	0.999999971	0.999980199	3877.1	1	0.00026	33963360	1.00	0.9136	0.914	46146	0.1735
Item: 221	Valve, Check.	0.999742108	0.999999971	0.999980199	3877.1	1	0.00026	33963360	1.00	1.0000	0.914	46146	0.1735
Control		0.999937125	0.999999943	0.999996490	15904.0	1	0.00006	13931940	8.00	0.1091	0.111	31599	0.0307
Item: 223	Valve, Control, N.C.	0.999922211	0.999999929	0.999997478	12854.8	1	0.00008	11260780	8.00	0.0000	0.080	31864	0.0221
Item: 224	Valve, Control, N.O.	0.999832761 *	1.000000000	0.999992325	3049.3	0	0.00017 *	52375670 *	0.00	0.0000	0.234	30528	0.0672
Expansion		0.999742991	1.000000000	1.000000000	1984.1	0	0.00026	34080094	xxx	xxx	xxx	xxx	0.0000
Item: 105	Valve, Expansion.	0.999742991 *	1.000000000	1.000000000	1984.1	0	0.00026 *	34080094 *	0.00	0.0000	xxx	xxx	0.0000
Gate		0.999827547	0.999999888	0.999999642	17394.5	3	0.00017	50792032	5.67	0.8333	1.135	3174502	0.0031
Item: 225	Valve, Gate, N.C.	0.999421886	0.999999934	0.999998647	1729.3	1	0.00058	15148344	1.00	1.0000	0.603	445540	0.0119
Item: 226	Valve, Gate, N.O.	0.999872337	0.999999883	0.999999752	15665.3	2	0.00013	68613876	8.00	2.0000	2.429	9801982	0.0022
Globe		0.999980570	1.000000000	0.999921533	26248.0	0	0.00002	45084720	xxx	0.9954	0.995	12685	0.6874
Item: 227	Valve, Globe, N.C.	0.999975654 *	1.000000000	0.999901776	20947.4	0	0.00002 *	35980272 *	0.00	1.0000	0.997	10149	0.8604
Item: 228	Valve, Globe, N.O.	0.999903788 *	1.000000000	0.999999612	5300.5	0	0.00010 *	91044470 *	0.00	0.0000	0.400	1031837	0.0034
Plug		0.990331504	0.999997992	0.999997984	15233.3	148	0.00972	901648.3	1.81	0.0476	1.592	789609	0.0177
Item: 232	Valve, Plug, N.C.	0.986191497	0.999997832	0.999997819	8845.9	123	0.01390	630001.6	1.37	0.0000	1.174	538126	0.0191
Item: 233	Valve, Plug, N.O.	0.996093704	0.999998213	0.999998213	6387.4	25	0.00391	2238150.	4.00	0.0000	4.000	2238151	0.0157

CATEGORY	CLASS	Reliability	Inherent Availability	Operational Availability	Unit Years	Failures	Failure Rate (Failures/Year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ Year
Reducing		0.998490771	1.000000000	0.999972616	337.7	0	0.00151	5799905.	xxx	0.4939	0.494	18036	0.2399
Item: 234	Valve, Reducing, Makeup Water.	0.998490771 *	1.000000000	0.999972616	337.7	0	0.00151 *	5799905. *	0.00	0.0000	0.494	18036	0.2399
Relief		0.998671145	0.999999696	0.999994763	752.0	1	0.00133	6587760	2.00	0.1796	0.190	36196	0.0459
Item: 235	Valve, Relief.	0.998671145	0.999999696	0.999994763	752.0	1	0.00133	6587760	2.00	0.0000	0.190	36196	0.0459
Suction		0.998214603	0.999998521	0.999994094	2238.4	4	0.00179	4902090	7.25	0.5358	0.698	118123	0.0517
Item: 181	Valve, Suction.	0.998214603	0.999998521	0.999994094	2238.4	4	0.00179	4902090	7.25	1.0000	0.698	118123	0.0517
Valve Operator		0.992808232	0.999991177	0.999971677	9975.4	72	0.00722	1213674	10.71	1.0564	1.469	51860	0.2481
Electric		0.990159307	0.999979209	0.999934083	3640.2	36	0.00989	885794	18.42	0.9823	1.400	21245	0.5774
Item: 229	Valve Operator, Electric.	0.990159307	0.999979209	0.999934083	3640.2	36	0.00989	885794	18.42	1.0000	1.400	21245	0.5774
Hydraulic		0.915817948	0.999969884	0.999601804	68.2	6	0.08794	99616	3.00	2.1569	2.204	5534	3.4882
Item: 230	Valve Operator, Hydraulic.	0.915817948	0.999969884	0.999601804	68.2	6	0.08794	99616	3.00	2.0000	2.204	5534	3.4882
Pneumatic		0.995224402	0.999998361	0.999997541	6266.9	30	0.00479	1829941.	3.00	0.9783	1.776	722345	0.0215
Item: 231	Valve Operator, Pneumatic.	0.995224402	0.999998361	0.999997541	6266.9	30	0.00479	1829941.	3.00	1.0000	1.776	722345	0.0215
Voltage Regulator		0.964377637	0.999690405	0.999644857	358.4	13	0.03627	241506.4	74.77	0.3333	2.523	7103	3.1110
Static		0.964377637	0.999690405	0.999644857	358.4	13	0.03627	241506.4	74.77	0.3333	2.523	7103	3.1110
Item: 238	Voltage Regulator, Static.	0.964377637	0.999690405	0.999644857	358.4	13	0.03627	241506.5	74.77	0.0000	2.523	7103	3.1110
Water Cooling Coil		0.999577258	0.999999879	0.999993176	4730.0	2	0.00042	20717496	2.50	0.2558	0.260	38084	0.0598
Fan Coil Unit		0.999577258	0.999999879	0.999993176	4730.0	2	0.00042	20717496	2.50	0.2558	0.260	38084	0.0598
Item: 239	Water Cooling Coil, Fan Coil Unit.	0.999577258	0.999999879	0.999993176	4730.0	2	0.00042	20717496	2.50	0.0000	0.260	38084	0.0598

*Time truncated, chi squared, 60% single-side confidence interval.